Water Quality Management of Contaminated Areas and its Effects on Doses from Aquatic Pathways

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Abstract. A critical analysis of remedial actions performed in the Chernobyl close zone are presented in term of effectiveness to dose reduction and money expenditure.
The Chernobyl experience proved the need to consolidate the international water protection capacity on the basis of scientific knowledge which should exclude inefficient use of national resource. Strategical and technological interventions on water quality management need to be revised on the base of the experience gained after the 1986 accident.
The lesson learned from the Chernobyl experience has to be used as a key element in the adoption of a strategy of water bodies management. Remedial actions have to be based with an integrated approach considering:

- dose reduction;
- secondary environmental effects of countermeasures;
- synergisms of radionuclides and countermeasure applications with other toxicants;
- social and economical factors of the contaminated areas.

1. Introduction

Surface and ground water resources of Ukraine, Belarus and the Russian Federation represent a vital problem for nearly 150 million population of these regions. After the Chernobyl accident, 8.5 million people living in the Dnieper basin became recipients of radionuclides through direct consumption of water from the Dnieper river-reservoir system and more than 30 million through irrigation and fishery.

Most of the radioactive fallout originated from the Chernobyl accident was deposited within the Dnieper River drainage basin that lies adjacent to the Chernobyl nuclear power plant site. This territory forms an extensive area from which contaminated run-off flows downstream through the Pripyat and Dnieper River systems across the Ukraine to the Black Sea (Figure. 1).

The analysis of water remedial actions carried out to minimize and mitigate water bodies, can provide an unique opportunity for decision makers who are working in other extensively contaminated regions, to optimize their approaches to surface and groundwater protection. Most engineering measures inside the Chernobyl 30-km exclusion zone were focused on prevention of secondary contaminations of the Pripyat river and the Kiev reservoir.

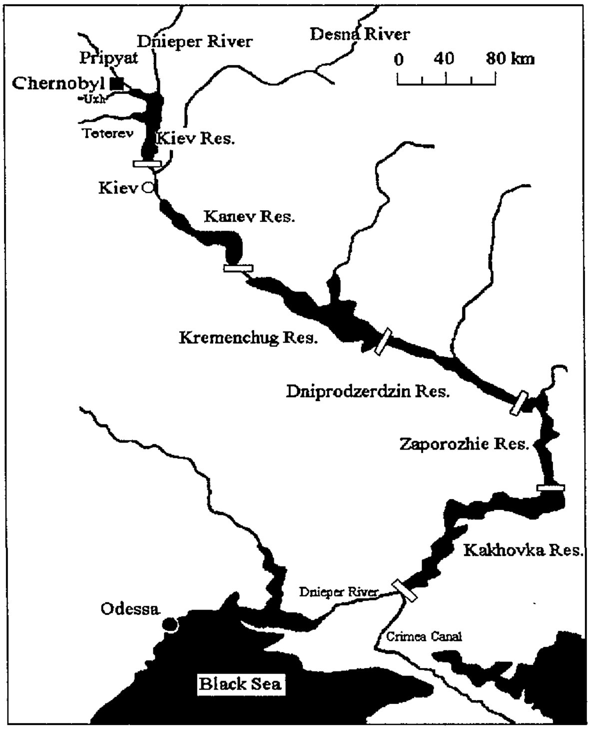

Fig. 1. The Dnieper Cascade

This paper describes nine years of mitigative measures applied on contaminated water bodies surronding the 30 km exclusion zone. The activities performed demonstrated that effectiveness of mitigative measures depends, not only on proper application of technology, but also on selection of projects offering significant risk reduction potential. In a limited national economy, environmental mitigative projects must maximize risk reduction and cost effectiveness avoiding the risk of ineffective use of national resources.

2. Radioactive Contamination of Water Bodies Located in the Chernobyl Evacuated Zone and of the Dnieper cascade

Most of the radioactive material released during the accident was deposited on the watershed areas of the Dnieper river (as well as the Pripyat catchment), heavy polluting large territories in the vicinity the Chernobyl nuclear power plant [1] [2] [3]. At present, inside the Chernobyl close-in zone, a large amount of radioactive materials is concentrated. Part of this material is constituted by soils of the catchment areas or, by water and bottom sediments from the lakes and the Chernobyl cooling pond, as result of the contamination of 1986. More than 3,7 x 10^{14} Bq of ^{90}Sr and about 7.4 x 10^{12} Bq of Pu are deposited in the flood plain areas that can be flooded during each spring and in the soils of polder areas in 30 km zone, that are annually inundated during snowmelt and rain-fall periods. Huge amount of radioactive wastes are located in shallow underground waste disposal sites, contacting ground water flows that move in direction towards the Pripyat river and to other directions [4] [5].

The watershed areas of the Pripyat and Dnieper rivers constitute the main potential secondary sources of ^{137}Cs and ^{90}Sr to the Dnieper cascade and to the Black sea [6]. Monitoring data indicate that ^{137}Cs and ^{90}Sr have different behaviour in the Dnieper system. Since 1986 the amount of radiocaesium transported within the system decreased continuously. On the contrary no significant decreasing has been observed for ^{90}Sr and its migration in hydrologic systems is considered to be a major long-term problem [7]. The different behaviour of these radionuclides is attributable to the fact that radiocaesium in soils is strongly sorbed by clay minerals, while strontium is in highly mobile chemical forms.

A second source of radioactive contamination of the Dnieper cascade is due to the groundwater contamination resulting from the wastes buried in shallow sands and trenches in the evacuated zone around Chernobyl. At present the concentration of ^{90}Sr in most of the superficial groundwater tables located in the 30 km zone, exceeds the permissible level (3.7 Bq l^{-1}). More serious situation has been observed in the shallow groundwater tables near the temporary waste disposal sites (at a distance of 5 km from the reactor), where the highly contaminated pine trees of the "Red Forest" were buried in 1987. In this particular case, where groundwater is contacting radioactive wastes, the 1994 monitoring data indicated, mean values of ^{90}Sr concentrations of 100 Bq l^{-1} and in some cases higher than 1000 Bq l^{-1}. Despite these levels of contamination, radionuclide transport to river through the groundwater pathways, contribute only marginally to the off-site radiological risk. In fact, groundwater flow is very slow and its contribution to river contamination is expected to occur not before 10-15 years.

In addition, also the infiltration into the Pripyat river, of contaminated water from the cooling pond of Chernobyl nuclear plant, has as a consequences the increase of river water contamination during low water seasons.

These are the sources of radioactivity that contribute to the contamination of the Dnieper cascade. Since 1986 a radiological monitoring system has been setup by the Ukrainian Hydrometeorological Institute along the Dnieper cascade, to assess the long-term impact of the Chernobyl accident on this system. Samples of water were regularly collected at several transects in the Pripyat river (Chernobyl cross-section), in the Uzh river (before its confluence into the Pripyat river), in the Dnieper river (before its input in the Kiev reservoir) and at the output of the six large artificial reservoirs (Kiev, Kanev, Krementchug, Dneprodzerdzinsk, Zaporozhye, Kakhov) [8].

The highest level of radioactivity in the water of the Pripyat river was observed during the initial period after the accident. The radionuclide contents in water exceeded in some cases the permissible levels. The data show from 1987 to 1994 a general decreasing of the radionuclide content in the river. As the chronological data indicate, ^{137}Cs values (dissolved and particulate phases) are lower than those for ^{90}Sr and usually the deviation of radionuclides from the linear trend is strictly corresponding to water discharge. A close relationship was found between ^{90}Sr and river water discharge (correlation, r^2=51%). Peaks of ^{90}Sr correspond to spring flooding in the areas located within 5-10 km around Chernobyl [8].

Also the data of the radionuclides inflowing into the Kiev reservoir (Fig. 2) suggest a close relationship between ^{90}Sr values and water discharge, while ^{137}Cs values are less dependent on surface hydrology. The increase of ^{90}Sr content in water is evident during the main spring floods, generated by snow melting [8].

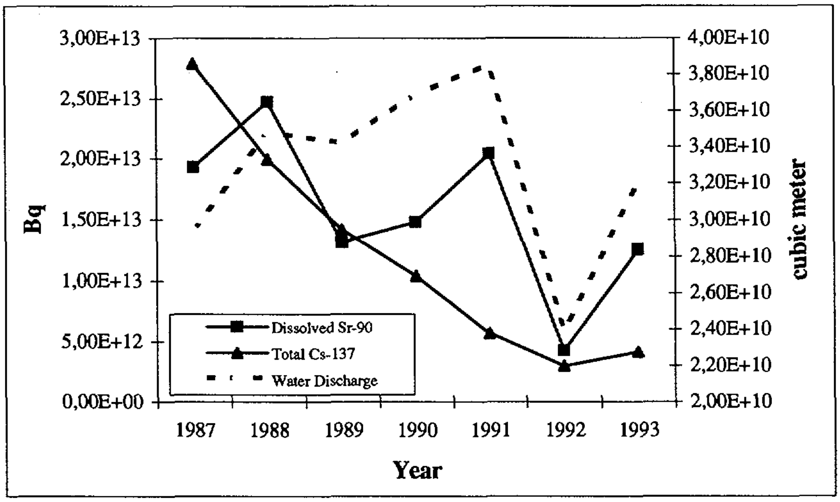

Fig. 2. Water discharge volume (m^3), total ^{137}Cs and dissolved form of ^{90}Sr (Bq) inflowing into the Kiev reservoir (1987-1993)

Most of the ^{137}Cs originated in the watershed of Pripyat and Dnieper rivers is accumulated in bottom sediments of the Kiev reservoir. The Kiev reservoir being characterized by low water velocities and high sedimentation rate has been revealed to operate as trap for ^{137}Cs transported in the particulate phase [9].

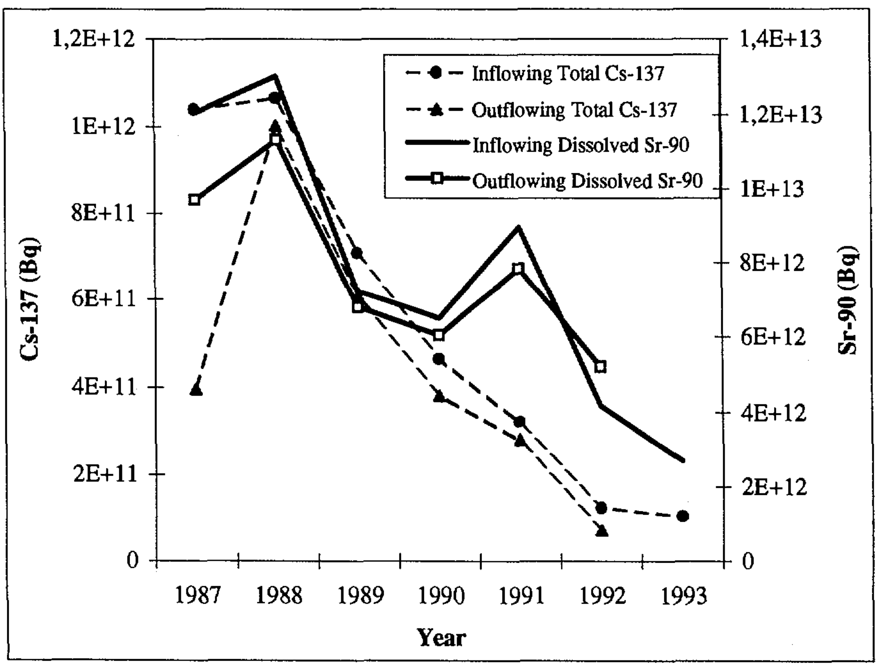

Fig. 3. ^{137}Cs and ^{90}Sr (Bq) inflowing and outflowing from the Kakhov reservoir (1987-1993)

Moving downstream to the series of reservoirs along the Dnieper cascade system, the balance of ^{137}Cs and ^{90}Sr show a similar trend than that found in the Kiev reservoir. The data of radionuclides outflow from the last reservoir of the Dnieper cascade (Kakhov reservoir) reported on Figure 3, show that ^{137}Cs values are an order of magnitude lower than those for ^{90}Sr. Two peaks are evident in the ^{90}Sr values, corresponding to 1988 and 1991 spring floods in Pripyat river watersheds. The total ^{137}Cs outflowing from the last reservoir in the period 1987-1993 (2.73 TBq) represents only 3% of the ^{137}Cs that entered the Dnieper cascade (85 TBq) in the same period. In contrast, the dissolved form of ^{90}Sr that reached the Black sea (46.8 TBq) from 1987 to 1993 represents the 43% of the amount of the radionuclide that entered the Dnieper river-reservoirs system (109 Tbq) [8].

These data confirm a long-term input of ^{137}Cs and ^{90}Sr, from the northern heavily contaminated areas, into the Dnieper and Pripyat rivers. From these rivers, most of the ^{137}Cs is distributed along the six artificial reservoirs composing the Dnieper cascade system, while the dissolved form of ^{90}Sr reach more easily the Black sea.

In conclusion, the radioactive contamination of the Dnieper cascade is mainly caused by direct surface water interactions with contaminated floodplain and catchment soils. At present the potential contribution of groundwater sources are expected to account for about 2 to 5% of the total release to the Pripyat river [7]. The present radiological situation of the Dnieper cascade, is the result of the combined effect of natural secondary contamination processes and the effects of the remedial actions performed in the contaminated areas since 1986.

3. Analysis of Remedial Actions Performed along the Dnieper Cascade

Since the Chernobyl accident, engineering and administrative countermeasures have been directed to protect from secondary radioactive contaminations, the main aquatic system of Ukraine (Dnieper river-reservoirs system), in order to reduce radioactivity dose for population living in Dineper basin, downstream the Chernobyl area.

The water protective actions were carried out in the following periods:

- Emergency phase (2-3 months after the accident);
- Early intermediate phase (from summer 1986 to 1988);
- Later intermediate phase (from 1989 to 1991).

3.1. Emergency phase (2-3 months after the accident)

Countermeasures during this period were mainly based on administrative decisions. The main actions are following reported:

- attempts to regulate the flows of contaminated water through the Kiev reservoir dam;
- increasing of the use of ground water sources for municipalities purpose (avoiding where possible the use of contaminated surface water);
- construction of supplementary ground water wells;
- purification of drinking water in municipal water treatment plants.

Most of these actions have been adopted without any cost-benefit analyses and were mainly influenced by social factors as emotional situation and pressure of the population living on affected areas. In this way a lot of national resources were spent, but in term of effectiveness to dose reduction and money expenditure, the results were extremely limited.

Some of the remedial actions were also applied without an adequate interpretation of the monitoring data. In a conflictual situation between scientists and decision makers, the first assessment of the adsorption-desorption kinetic parameters for radionuclide liquid-solid interactions was erroneously determined and consequently, the wash-off coefficients were overestimated. As a result many useless water protective actions were adopted in the first months after the accident. As example, the discharge into the rivers flowing downstrean Chernobyl of unprocessed zeolite material.

On early May 1986, several actions were also done at the Kiev reservoir dam. The surface gates were opened and closed the bottom ones. Unfortunately, these operations were adopted on the base of a lack of hydrologic knowledges, considering that the most clean water were on the surface of the reservoir. But, during the first weeks after the accident, the deeper water of the reservoir were less contaminated and the actions at the Kiev reservoir dam have had as a consequence an increase of the dose to population living downstrean to the reservoir, in the period in which the main exposure took place from drinking water intake.

3.2. Early intermediate phase (from summer 1986 to 1988)

During the 1986 summer, protective dikes of several km were constructed along the Pripyat river with the purpose to trap the run-off of contaminated material from the towns of Chernobyl and Pripyat. These actions were not effective to controll the run-off from the broad landscapes.

In the same period (spring-summer) several canal bed traps were dredged in the bottom bed of the Pripyat river, to increase the river's cross-section and to reduce water velocity. The expected result was to favorize the sedimentation of the contaminated suspended material in the bulk flow according to the Stock's law. Subsequent investigations [10] [11] showed that these traps were ineffective, because the size of these suspended particles were too fine to be settled in a river as Pripyat, characterized by huge water discharges and turbolent flow conditions.

The cooling pond of Chernobyl nuclear power plant was also interested in the remedial actions performed in the early intermediate phase. A special drainage well was built around the damaged reactor, to isolate the cooling pond from the Pripyat river, with the main purpose to trap the infiltrating radioactive water. Up to now, this drainage system is not operating because many doubts arised as a consequence of its operation. Recent researches [6] indicate that pumping water from these wells to the cooling pond could cause problems in the balance of water and dissolved salts in the pond. A lot of national resources were spent for the realization of this project.

During this phase, an underground clay barrier was constructed between the Chernobyl reactor and the Pripyat River. This barrier was built to prevent the migration of contaminated ground water into the river. Additional studies showed that the migration of radionuclides through the ground flows was very slow and consequently the project was stopped.

From 1986 to early 1987, more than 100 zeolite-containing dikes were completed, aiming to adsorb radionuclides from smaller rivers and streams. Subsequent studies indicated that only 5% to 10% of ^{90}Sr and ^{137}Cs transported by the rivers were adsorbed by the zeolite barriers within the dams. In addition, the streams that were dammed during this activity contributed only with a few percent to the total flow of the Pripyat and Dnieper drainage basins. In 1987, the construction of new dams were stopped and it was decided to destroy most of the existing.

In 1987, after the evacuation of the local population and the core of the damaged reactor was extinguished, the burial of contaminated soils, vegetation, debris etc, was used as mitigative measure. This was the case of the highly contaminated pine trees of the "Red Forest" (killed by the high levels of radiation), located at a distance of about 5 km from the reactor. These measures were deemed necessary to protect the "liquidators" and people working inside the exclusion zone, from high radiation doses. To this end all wastes were buried in shallow sands and trenches without any action to prevent the contamination of ground water. As a result, intense local ground-water contamination from these buried trees poses a large, long-term problem for environmental remediation and restoration.

3.3. Later intermediate phase (from 1989 to 1991)

A new phase of hydrologic remediation started after the summer flood of 1988. High water levels covered most of the contaminated flood plain and caused a secondary contamination of ^{90}Sr of the river systems. Modeling of surface hydrology indicated as a realistic, dangerous or "worst-case" scenario, that would cause the highest radionuclide concentration in rivers, a spring flood with a maximum discharge of 2000 $m^3 s^{-1}$ - a 25-percentile probabilistic flood. The model simulation of this "possible worst hydrological scenario", in which the Chernobyl exclusion zone would be significantly flooded, indicated a ^{90}Sr contamination of the water near Kiev and in the last reservoir of the Dnieper cascade (Kakhov reservoir), several times higher than in normal condition. But when in the computed results the washing-out processes were simulated with isolated radioactive sources on the flood plain, the ^{90}Sr concentration decreased in 2-4 times. Several approaches have been proposed and the potential effectiveness of each of them, to reduce radioactive radionuclide concentrations in the rivers, were simulated. Creation of dikes around the contaminated areas on the left (east) bank of the river was chosen as the best protective options. These measures, with additional decontamination of soils of the right bank and with a solution for the infiltration of cooling-pond water could significantly reduce the ^{90}Sr concentration at the downstrean boundary. The flooding events of January 1991 and summer 1993 confirmed definitively the simulated results [6] and consequently in 1992 the dikes were built. With this option, during the flooding of summer 1994, more than 3.7×10^{12} Bq of ^{90}Sr were prevented to be washed-out from the flood plain of the Pripyat to the Dnieper cascade. This event proved the need to consolidate the water protection strategy on the base of scientific knowledge which should exclude inefficient use of national resources. Engineering works were completed in 1993 in the Chernobyl close-in zone and at present time developement of future technological and strategical capacities on water protection are in progress.

4. Radiation Risk Assessment from Water Usage

The present level of radionuclides content in the Dnieper cascade water does not pose health risks. Analysis of ^{90}Sr migration via groundwater to surface water and down-river population centers shows that, radionuclide transport via the groundwater pathway has potential to contribute only marginally to the off-site radiological risk, which is governed by wash-out of radionuclides from the contaminated river flood plain and catchment areas by surface water during snow melt and rains. Groundwater contributes to rivers contamination for about 2 to 5% of the total release from terrestrial environment [7]. It has been estimated that also after 20 years from the accident, the groundwater will not significantly contribute to surface water contamination.

The technological possibilities to control the existing non point sources of radioactive contamination on a such large catchment scale as the Chernobyl area, are very limited. The optimization of a future strategy of water bodies management can be done only comparing human doses, that could be economized as result of engineering water protection and water remediation actions in the Chernobyl site. To optimize and substantiate a new concept of water protection, a huge research work has been done in term of risk assessment and cost-benefit analyses. The radiological monitoring data and the predicted radionuclide contents in the Dnieper's water up to 2056 year were used for the estimation of the committed collective internal doses from ^{90}Sr and ^{137}Cs to the population of the Dnieper's regions. The structure of committed dose (70 years intake), due to water usage, averaged for all water consumers living along the Dnieper system, is distributed respectively as 35, 40 and 25 % from drinking water, fish and irrigated products. This dose structure is different for the different regions of Ukraine. The studies also showed that annual averaged individual effective internal dose for different regions of Ukraine is very varied. In 1993 for instance, the water pathway contribution to the total radiation dose for the Kiev citizen was about 6% and ranged between 20 and 30% for people living in the southern region of Ukraine [5] [12].

Using the nominal probability coefficient 7.3×10^{-2} 1/Sv (ICRP-60), the number of stochastic cancer effects due to Dnieper water usage during 70 years were estimated. The results indicate about 200 cancer cases on 30 million people (70 years exposure) and about 60 persons during 1986-1992. Recalculation of dose values for all the exposed population, demonstrates that the averaged individual human radiation risk from Dnieper water use cannot be more than 1×10^{-5}. For some critical groups of water users, expected individual risk would be 4-5 and even more times higher. The implementation of the most effective water protective countermeasure can reduce 3-4 times the above radiation risk from water usage.

These results indicate a very low level of radiation risk due to water usage, if compared with others sources of radiation. It is necessary to point out that the stress component for radiation risk of population consuming radioactive contaminated water, is more dominant than the dose component effect. At present, the contribution to the radioactive dose for inhabitants of Kiev (via the water pathway) is likely to be small (a few percent) although it does increase to 10-20% for populations lower down the Dnieper river-reservoir system, where no other water sources are available and much more radioactivity from water enters the diet, as irrigation of food crops is extensive. However, as a recent study has shown, the popular conception within the population of Kiev is that radioactivity in water is equally important as food as far as the dose to man is concerned.

The future strategical and technological interventions on water quality management of the Dnieper cascade need to take into account also the synergisms of radionuclides and countermeasure applications with other toxicants. In fact, the Dnieper reservoirs are situated in industrial and agricultural areas, badly affected by great number of various industrial entreprises with backward technologies including chemical industry, metallurgy, energetics and misuse of pesticides in agriculture. Toxicological investigations showed the presence in water of other toxic substances with carcinogenic and mutagenic properties. In many cases, the origin of these substances is not defined and no information are available about their environmental behaviour. This aspect is a relevant factor to take into account when assessing risk for population on contaminated areas.

5. Conclusions

In spite of low level of exposure for population of Ukraine due to aquatic pathways, the radionuclides transfer by the water flow (mainly from sources situated in the Chernobyl zone) is the most relevant factor of the contamination of the Dnieper aquatic system. In the case of Chernobyl, where the sources of water radioactive contamination are determined, the realisation of a set of priority of water protective actions are recommended. However any countermeasures cannot be implemented without real benefits according with "ALARA" principles. On this basis the Ukrainian Authorities developed from 1993 a scheme of priority chain for water remedial actions. The future devolpment of countermeasures must assure that the ^{90}Sr concentration in the water of Pripyat river, downstream the boundary of the evacuated zone, not exceed the value of 2 Bq l^{-1}. On this basis, the following list of remedial actions has been suggested:

- development of a radioactive monitoring network for ground and surface water, inside and outside the Chernobyl evacuated zone;
- completion of diking on the highest contaminated flood plains, in the left and right side of Chernobyl plant. This action will keep back water and prevent flooding and it is estimated that it will possible to reduce to about 4-5 times the present annual wash-out of radionuclides;
- development of a project for the clean-up of the cooling pond, after the shutdown of the Chernobyl reactors;
- water regulation on the highly contaminated wetlands located in the Chernobyl site. This action has been suggested in agreement with Belarus to keep flooded peat bog areas against fire risk;
- construction of engineering and geochemical barriers around the waste disposal sites located in the Chernobyl zone.

The above mentioned countermeasures will allow to reduce the potential risk from water usage and they will also have a positive effects on the unnecessarily high levels of stress amongst the population living downstream Chernobyl and along the Dnieper cascade. The implementation of these remedial actions will require only several percent of the current financial budget of the Minchernobyl of Ukraine, directed to the liquidation of the consequences of the Chernobyl accident.

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