ASSESSMENT OF THE TREATMENT CAPABILITY AND OPTIONS TO ENHANCE THE PERFORMANCE OF THE DECONTAMINATION SYSTEM OF AQUEOUS RADIOACTIVE WASTE FROM CERNAVODA NPP

EVALUAREA CAPACITĂŢII DE TRATARE ŞI OPŢIUNI DE CREŞTERE A PERFORMANŢELOR SISTEMULUI DE DECONTAMINARE DEŞEURI RADIOACTIVE APOASE DE LA CNE CERNAVODĂ

Mirela DULAMA[1], Marius IORDACHE[2], Liliana SAMSON[3], Alexandru NEDELCU[4], Viorel TOBOSARU[5]

Abstract: *In CANDU plants, the decontamination of liquid waste is performed by the LRWS (The Aqueous Liquid Radioactive Waste System). The process is based on filtration and ion exchange, using a cellulose-ion exchanger premix. The study has estimated the treatment capacity of the product used at Cernavoda NPP, depending on the composition of the waste. The data obtained were validated experimentally and a calculation algorithm was developed to establish the volume of real waste that can be treated efficiently in the decontamination system installed at Cernavoda NPP. Also, the addition of an advanced treatment step, using selective ion exchangers, to the decontamination system, was studied.*

Keywords: radioactive waste, decontamination, ion exchange, nuclear power plant

Rezumat: *În centralele CANDU, decontaminarea deşeurilor lichide se realizează în sistemul LRWS (The Aqueous Liquid Radioactive Waste System). Procesul se bazează pe filtrare şi schimb ionic, utilizând un premix celuloză-schimbători ionici. Studiul realizat a estimat capacitatea de tratare a produsului utilizat la CNE Cernavodă, în funcţie de compozitia deşeului. Datele obţinute au fost validate experimental şi s-a elaborat un algoritm de calcul pentru stabilirea volumului de deşeu real care poate fi tratat eficient în sistemul de decontaminare instalat la CNE Cernavodă. De asemenea, s-a studiat completarea sistemului de decontaminare cu o etapă de tratare avansată utilizând schimbători de ioni selectivi.*

Cuvinte cheie: deşeuri radioactive, decontaminare, schimb ionic, centrale nucleare

[1] Dr., Institute for Nuclear Research Pitesti (ICN Pitesti), Technologies for Nuclear Energy State Owned Company (RATEN), Romania, e-mail: mirela.dulama@nuclear.ro
[2] Eng., Institute for Nuclear Research Pitesti (ICN Pitesti), Technologies for Nuclear Energy State Owned Company (RATEN), Romania, e-mail: marius.iordache@nuclear.ro
[3] Eng., Cernavoda NPP, Nuclearelectrica SA, Romania, e-mail: liliana.samson@cne.ro
[4] Eng., Cernavoda NPP, Nuclearelectrica SA, Romania, e-mail: alexandru.nedelcu@cne.ro
[5] Eng., Cernavoda NPP, Nuclearelectrica SA, Romania, e-mail: georgian.tobosaru@cne.ro

1. Introduction

The collection, storage, sampling, decontamination and controlled release of liquid radioactive waste generated, both in the operation of Cernavoda NPP, as well as in the maintenance, repair and decontamination activities, are carried out within the LRWS (The Aqueous Liquid Radioactive Waste System).

The LRWS has a decontamination unit installed which must ensure the reduction of the concentration of radioactivity in the effluent, below the guidelines established for environmental release. The decontamination unit operates based on precoat filtration and ion exchange processes. The LRWS decontamination subsystem must have the capacity to reduce the β/γ activity, within the prescribed limits, for a volume of 50 m^3 of liquid waste, during a day, taking into account the time required to set up the installation (loading/evacuation of the Ecodex premix).

Typically, the radioactivity of the liquid waste lay below the limit established for discharge, and in special situations, when decontamination is required, the liquid waste is treated by filtration / ion exchange. The radioactivity of the discharged effluent is continuously measured by a monitoring system (MEL), which automatically shuts off the discharging circuit when the limit value of $5x10^3$ Bq/L is reached. In this case, the waste waters are recirculated in the tank for analysis and resumption of decontamination [1, 2].

The research topic for the technical evaluation of the installation for decontamination of radioactive aqueous liquid waste from Cernavodă NPP was included in the R&D Program no. 5 of RATEN, at the proposal of Cernavoda NPP. Within the research theme the following activities have been performed: the decontamination efficiency was determined for the Ecodex premix, used in the operating conditions, specific to the filter installed in the LRWS; the compliance with the limitations imposed on the feed influent of the filtering and ion exchange unit was verified and solutions have been proposed for increasing the decontamination performance of radioactive aqueous liquid waste at Cernavoda NPP.

During the research activities, at the ICN Pitesti were transferred aqueous radioactive waste considered representative for the waste treated in the decontamination subsystem of the LRWS. The experimental tests carried out aimed to determine the decontamination capacity for the aqueous waste transferred from Cernavoda NPP, by using the Ecodex premix, under the parameters recommended in the Operation and Maintenance Manual of the ion exchange filter installed in the LRWS.

The studies carried out aimed at increasing the efficiency of decontamination, by maintaining in operation the ion exchange filter within the decontamination subsystem of radioactive aqueous liquid wastes from Cernavoda NPP and by maintaining the adsorbent material currently used.

2. Materials and methods

2.1. Treated aqueous radioactive waste

Depending on the origin and radioactive content, at Cernavoda NPP aqueous radioactive waste is collected segregated into three categories and stored in 5 tanks of 50 m^3 each [1, 2].

Radioactive liquid waste collected by LRWS is classified as follows [2, 3]:

- Level 1 liquid waste, resulted from the lavatories, showers, laboratories and the floor drainages from the service building. The γ activity concentration of these wastes is between 3.7×10^{-1} Bq/L and 3.7×10^{2} Bq/L, with an average value of 1.85×10^{2} Bq/L.

- Level 2 liquid waste, which may come from the heavy water enrichment tower, the equipment decontamination system, the floor drainage of the service building and the laboratories. The γ activity concentration of these wastes lies in the range 3.7×10^{2} Bq/L and 3.7×10^{4} Bq/L.

- Level 3 radioactive waste, resulting from the drainage systems of the reactor building, the spent fuel pool (BCU), the waste ion exchangers storage tanks, the BCU drainage wells / the reactor building/ service building and the D_2O systems area. The γ activity concentration of these wastes lies in the range 3.7×10^{4} Bq/L and 3.7×10^{6} Bq/L.

Level 3 radioactive liquid waste can be sent directly to the decontamination unit without being discharged into the LRWS [2].

Typically, Level 2 and 3 radioactive liquid wastes are collected together, resulting in activity between 3.7×10^{1} Bq/L and 3.7×10^{5} Bq/L, with an average value of 1.85×10^{3} Bq/L [2].

The wastes transferred from the Cernavoda NPP for decontamination to the ICN Pitesti were analyzed physico-chemically and radiologically to determine the parameters that can influence the treatment. The main radioactive contaminants consist of colloidal particles and ionic species dissolved in demineralized water, decontamination requiring treatment by decantation, filtration and ion exchange.

2.2. LRWS's ion exchange filter

The system of decontamination of aqueous liquid waste from CNE Cernavoda is installed to reduce the content of radioactive particles from any effluent to acceptable values, recommended by the Department of Radioprotection and imposed by CNCAN (National Commission for Nuclear Activities Control).

The equipment used is a filter coated with a premix of special natural fibers, for retaining colloids, and a mixed bed resin used for the retention of ionic species by ion exchange. The preparation of the filtering material consists of mixing the premix with demineralized water, in a tank of ~ 230 liters and feeding it into the filter by using a centrifugal pump with the flow rate of 4.5 L/s [2].

The subsystem has the daily capacity to reduce the beta-gamma activity of the liquid waste from a tank, below the accepted limits, taking into account the time required to prepare the installation. The content of the tank can be treated in 8 hours by recirculation, considering an average flow rate of 3.8 L/s and a decontamination factor ranging from 10 (at the beginning of the cycle) to 2 (at the end of the cycle). At these average values of the flow rate and of the decontamination factor, every 1-1.5 hours the radioactivity of a volume of 35 m^3 of liquid waste is halved [2].

If the radioactivity of the liquid waste is, entirely, in ionic form, the decontamination capacity depends on the total concentration of the dissolved species (TDS). If the TDS value is high, the filter can retain only part of the dissolved solids, therefore only part of the radioactivity contained. In such situations it is compulsory to repeat the treatment through the ion exchange filter until the accepted concentration is achieved [2].

The ion exchange filter is the precoat-filtration unit of LRWS from Cernavoda NPP. During the preparation stage of the filtering surface by coating with resin-cellulose premix, a suspension of 10 kg of Ecodex in 900 liters of water is recirculated for 10 minutes, with a flow rate of 75 L/min. In the waste treatment stage, 20 m^3 of waste is recirculated for 8 hours, with a flow rate of 3.8 L/s [2,3,4].

Ecodex, manufactured by Graver Technologies Company (USA), is a homogeneous mixture of Powdex® ion exchange resins (strong acid cationite + strong basic anionite) and cellulose fibers [5].

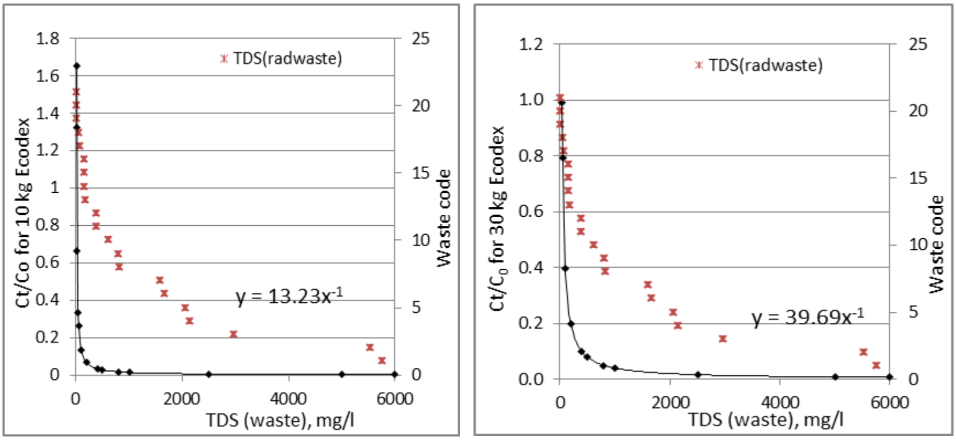
2.3. Determination of the decontamination capacity for Ecodex

The exchange capacity (*K)* of the Ecodex commercial product was calculated based on the specifications in the product data sheet [5]. Thus, the exchange capacity of the premix used at Cernavoda NPP for decontamination of aqueous radioactive waste is maximum 0.85 meq NaCl/g of product.

Figure 1 shows the treatment capacity of the Ecodex®P-201-H premix, depending on the ionic strength of the supplied waste, considering that the efficiency of using the exchange capacity is 90%.

On the same graphs, the TDS values were plotted for the 21 containers of radioactive aqueous waste that were transferred from Cernavoda NPP to be treated at ICN Pitesti. Drawing a parallel to the OY 'axis through the point representing the TDS value of the waste, the intersection point of the graph indicates the maximum theoretical volume, of that type of waste, which can be treated by 10 kg Ecodex (fig. 1a) and 30 kg Ecodex (fig. 1b), respectively.

Estimated values were verified experimentally for solutions with pH 6 and 9, by determining the distribution coefficients for sodium chloride (NaCl) solutions with concentrations in the range 0.01 g/L - 1 g/L, at different *solid:liquid* ratios, and in static contact regime (*in batch*).



a) b)

Figure 1. Variation of the treatment capacity (theoretical) with the ionic strength of the waste, for Ecodex product (C_t –treatment capacity, C_0- treatment capacity target)

Monitoring of the ion exchange process was based on TDS measurement.

Checking of the equivalence between the measured TDS and the NaCl concentration was performed by conductometric titration with Ag nitrate. A very good correlation was observed between the measured TDS and the NaCl concentration in the solution, determined by conductometric titration.

2.4. Estimation of the treatment capacity of the decontamination facility for radioactive aqueous liquid waste from Cernavoda NPP

Decontamination tests were performed, by simulating the operation of the ion exchange filter from the LRWS decontamination subsystem, installed at Cernavoda CNE.

As in the real system, the waste was recirculated for 8 hours, with pH, conductivity, TDS and radioactive concentration being determined periodically.

The tests tracked the influence of pH and dissolved salts (TDS) on the treatment capacity of the Ecodex premix fed into the ion exchange filter.

Testing of the efficiency of radioactive waste decontamination, using the ion exchange filter, was performed with a real radioactive waste with neutral pH, TDS = 200 mg/L, over $5x10^3$ Bq/L Cs-137 and Co-60, respectively.

Figure 2 shows the efficiency of using the theoretical capacity of exchange for dynamic regime tests. The value of 200 mg L corresponds to the test with real radioactive waste.

Knowing the maximum value of the exchange capacity, the Ecodex premix surplus/deficit was calculated in the tests that simulate the flow rate in the Cernavoda NPP ion exchange filter.

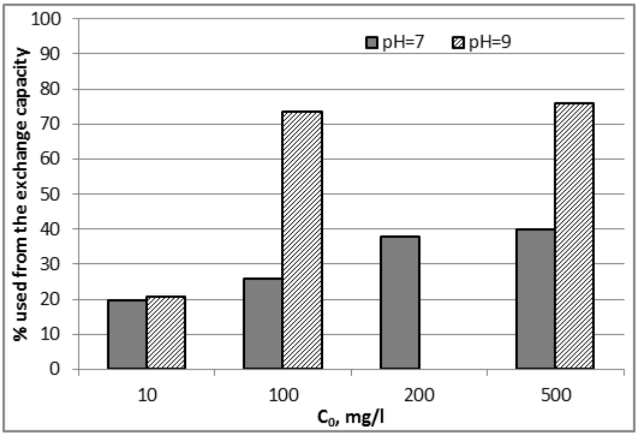


Figure 2. The efficiency of using the theoretical capacity of exchange in dynamic regime tests (C_0- initial TDS)

Based on the obtained experimental results it was concluded that the improvement of the ion exchange filter performance can be made either by increasing the amount of adsorbent material used, while maintaining the treatment capacity, or by reducing the treatment capacity, while maintaining the amount of adsorbent material. In this respect, correction, factors were calculated, depending on the adsorbent's exchange capacity, practically determined for the studied system. By applying these correction factors, one can calculate the quantities of Ecodex needed for the treatment of a volume of 20 m^3 real waste or the volumes of real waste that can be treated by using 10 kg of Ecodex.

2.5. Testing of the proposed solution to improve the performance of the aqueous liquid waste decontamination system

Two experimental tests were performed to verify the proposed technical solution. The aim was to increase the performances of decontamination of radioactive aqueous liquid waste and the efficiency of the retention of radioisotopes of cesium.

The dynamic regime tests simulated at the laboratory scale the flow regime of the ion exchange filter from the Cernavoda NPP, reducing the treatment capacity of the system and maintaining the amount of adsorbent material.

It has been demonstrated previously that, when designing the installation, the composition of the treated waste must be taken into account. Thus, in the first experiment the volume of treated waste was calculated, starting from the concentration of dissolved salts (TDS) in the waste and considering that 100% of the exchange capacity calculated for the used Ecodex sorbent was used. The test was performed with a real radioactive waste with the pH=7, TDS=230 mg/L and over $5x10^3$ Bq/L Cs-137 and Co-60, respectively.

According to the stated reasoning, the decontamination plant at Cernavoda NPP should treat a volume of 2.44 m^3 waste with the given composition, considering the theoretical exchange capacity equal to the nominal exchange capacity.

The experimental procedure was established so that the characterization of the waste during the test to correspond for the entire volume of waste in the tank of the installation, not only, to the waste at the exit of the ion exchange filter. This way of operation implies the interruption of the operation during the acquisition of the gamma spectra, when using a fixed analyzer. The test was carried out over three days, to ensure the 8 hours of decontamination, respecting the data acquisition algorithm established in the experimental procedure.

The testing of the proposed technical solution, for the efficient decontamination of radioactive waste, was repeated in the second experiment, with a real radioactive waste with a similar composition. When establishing the treatment capacity of the installation, the use of about 70% of the exchange capacity, calculated for the Ecodex sorbent, was assumed. In this case, the Cernavoda NPP decontamination plant should treat a volume of 1.3 m^3 waste with the given composition, while maintaining the amount of adsorbent material currently used, or it could treat roughly 15 m^3 of waste, by using below 130 kg premix Ecodex.

In this experiment, to track the evolution of the radioactivity of the waste during the test, an in-situ gamma spectrometry analyzer was used. The decontamination test lasted 8 hours, by running continuously.

3. Results and discussions

3.1. Efficiency of decontamination of aqueous radioactive waste according to composition

The experimental verification of the treatment capacity for Ecodex was done in static and dynamic regimes. It was observed that the waste should contain only a few tens of mg/L dissolved salts so that 10 kg of Ecodex could provide the exchange capacity needed for decontamination. The influence of pH and dissolved salts (TDS) on the treatment capacity of 10 kg Ecodex, in dynamic regime, is shown in Figure 3.

The dynamic regime tests simulated at the laboratory scale the flow regime of the ion exchange filter from Cernavoda NPP, respecting the thermodynamic parameters of the decontamination process.

The decontamination factors (DF) obtained experimentally in the simulated tests with NaCl solutions were lower than 1.86.

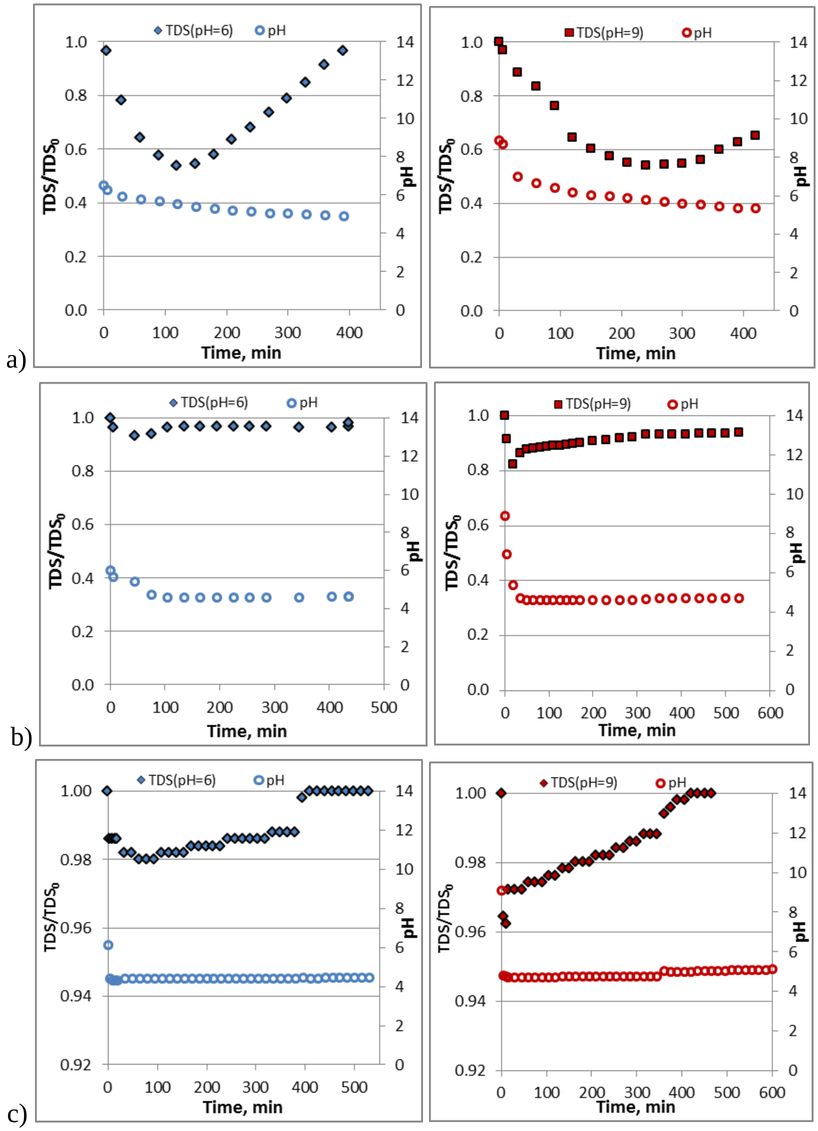


Figure 3. TDS and pH variation for dynamic regime tests at pH 6 and 9(TDS_0– initial TDS) a) Solution 0.01 g/L NaCl; b) Solution 0.1 g/L NaCl; c) Solution 0.5 g/L NaCl

It was observed that the best decontamination is obtained after 2 hours (pH≈6) and 4 hours (pH = 9) respectively of recirculation, and the systems with adsorbent deficit are saturated quickly.

Testing the efficiency of radioactive waste decontamination, using the filter installed in LRWS, was performed with a real radioactive waste, with TDS = = 200 mg / L.

According to estimates, the system configuration is efficient for a waste with a maximum of 25 mg/L dissolved salts, thus treating the waste containing 200 mg/L dissolved salts has been done with adsorbent deficit.

Figure 4 shows the results obtained for the treatment of radioactive waste with a dissolved salt content (TDS) of 200 mg/L.

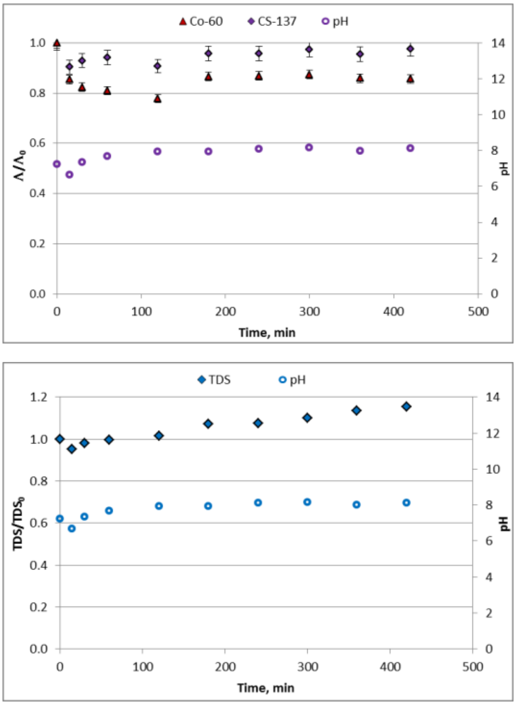


Figure 4. Variation of concentrations of radioactive species and TDS when simulating the filter operation (Λ - radioactivity concentration, Λ_0 – initial radioactivity concentration)

It was observed that the maximum values of the obtained decontamination factors ($FD_{Co\text{-}60}$=1.3, $FD_{Cs\text{-}137}$=1.1, $FD_{Cs\text{-}134}$=1.1 were reached after 2 hours of recirculation, subsequently decreasing sharply.

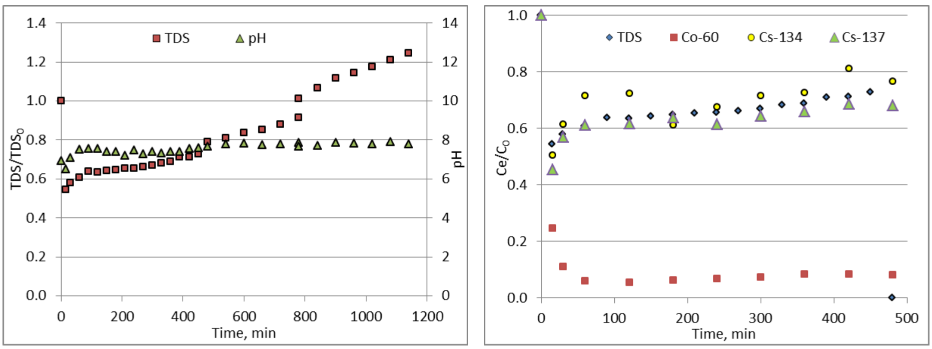
3.2. Options to increase the performance of the decontamination system of aqueous radioactive waste from Cernavoda NPP

Increasing the efficiency of decontamination, while maintaining the ion exchange filter in operation with the currently used adsorbent material, can be achieved either by reducing the treatment capacity of the plant or by increasing the amount of adsorbent material used. The recommended technical solution makes a compromise between the two variants, proposing to establish a maximum permissible height for the adsorbent layer deposited on the septum and to calculate the filter treatment capacity according to the total dissolved salt content of the waste from the decontamination plant tank.

The results of the tests performed to verify the proposed technical solution are presented below.

I. *System dimensioned for using 100% from K(theoretical exchange capacity)*

Figure 5(a) shows the evolution in time of the concentration of ionic species dissolved in the waste, during the performed test. The monitoring of the physico-chemical parameters was done over a period of 20 h to verify the influence of the extended contact time on the efficiency of ion exchange.



(a) (b)

Figure 5. Physico-chemical properties of effluent (a) and sorption kinetics (b) in the test dimensioned for 0,056g NaCl/g Ecodex (c_e- concentration, c_0- initial concentration)

It is observed that the decontamination factor, related to TDS, reaches the maximum value in the first half hour, after which it decreases slightly, stabilizing for the next 8 hours.

In this configuration, the increase of contact time (treatment duration) did not lead to the improvement of ion exchange.

Figure 5(b) shows the kinetics of dissolved salt sorption (TDS) and radioactive isotopes present in the studied waste.

A similarity is observed between the evolution of the content in dissolved salts and the concentration of cesium radioisotopes, which validates the estimates made previously based on TDS. The decontamination factor, relative to Cs-137, reaches the maximum value in the first half hour, after which it decreases slightly.

In the case of cobalt, the decontamination factor reaches its maximum after 2 hours of recirculation, and then gradually decreases.

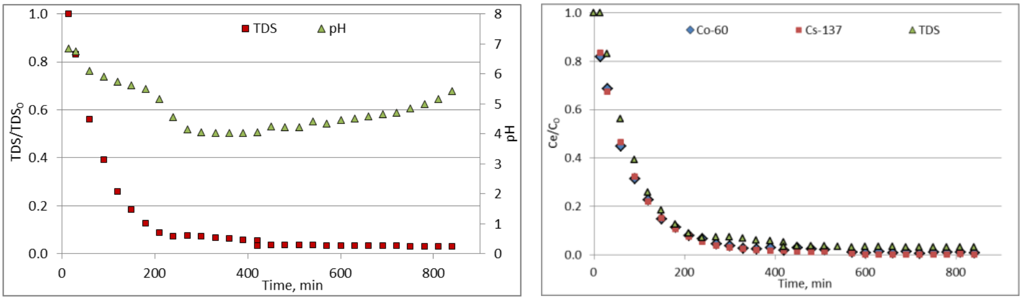
II. *System dimensioned for using 70% from K(theoretical exchange capacity)*

When configuring this test, it was taken into account that in the experiments performed previously, the entire available exchange capacity was never used.

The test was sized by combining the two variants of improvement for the ion exchange filter. Thus, the amount of adsorbent material used has been increased (about 13 times) and the volume of treated waste has been decreased by 20%.

Figure 6(a) shows the evolution over time of the ionic species concentration dissolved in the waste, during the test carried out with excess adsorbent.

Figure 6(b) shows the kinetics of dissolved salt sorption (TDS) and radioactive isotopes present in the studied waste. It is observed that the process kinetics is the same for Cs-137, Co-60 and dissolved salts, in the excess sorbent dimensioned test.



(a) (b)

Figure 6. Physico-chemical properties of effluent (a) and sorption kinetics in the dimensioned test for 0.035 g NaCl/g Ecodex

It is observed that the decontamination factor, related to TDS, increases exponentially in time.

In this configuration, the extension of the waste-sorbent contact time led to the improvement of ion exchange.

The radioactive decontamination factor reaches the maximum value at the end of the test, and after 8 hours of recirculation it is more than 40.

Figure 7. shows the exchange capacity used, compared to the available exchange capacity. It was observed that after 8 hours of recycling 96% of the available exchange capacity was used.

The test performed at the laboratory scale involves the deposition on the septum of a filter layer with a thickness of 100 mm.

The option of increasing the decontamination performances of the ion exchange filter, by maintaining the treatment capacity and increasing the amount of adsorbent, does not comply with the technical specifications indicated by the manufacturer for operating the equipment. Thus, the only feasible option of increasing the decontamination performance remains those based on the maintenance of the amount of adsorbent currently used and the reduction of the treatment capacity.

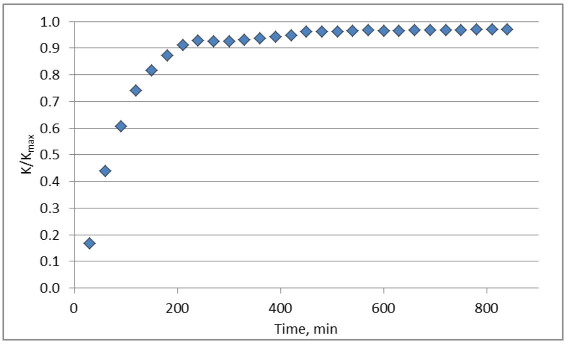


Figure 7. The efficiency of using the theoretical exchange capacity [3]

For this purpose, a calculation algorithm has been developed to determine the actual volume of waste that can be treated by 10 kg Ecodex. Thus, the volume of waste (in m^3) that can be treated in the LRWS filter, loaded with 10 kg Ecodex, is given by the ratio: F/TDS *[mg/L]*, where *F* is a correction factor established according to the decontamination factors which are intended to be obtained.

3.3. Recommendations for the improvement of decontamination of radioactive liquid waste at Cernavoda NPP

The upgrade of the system for decontamination of aqueous waste from Cernavoda NPP has been studied by considering the addition of an advanced treatment stage using selective ion exchangers. The major advantage of using highly selective ion exchange media is the large reduction of the volume of waste destined for final storage, volume determined by the efficiency achieved during the decontamination stage.

The selective ion exchangers studied in the paper are commercial products, tested in nuclear applications. Some of these can be used as granular filter media, arranged in a fixed bed, or in powder form, impregnated on filter materials and used in filter cartridges. Also, processes have been developed that use selective ion exchange materials in the form of fine powder deposited on a support matrix, in precoated filters.

The highly selective ion exchangers recommended are manufactured by:

- Fortum Nuclear Services, Finland (*CsTreat*®, SrTreat® and CoTreat®**)**
- UOP LLC A Honeywell Company, SUA (IONSIV® IE-911, IONSIV® R9160/R9120)
- 3M Company, SUA (SSC™)
- Graver Technologies Company, SUA (RADEX®Cs/RADEX®Co/ RADEX®Sb FLIP).

The commercial offer of highly selective ion exchange materials is quite limited, and of the products recommended based on the results presented in the literature, part is no longer produced due to the reduced sales market or cannot be acquired because the manufacturer does not provide the product for testing.
It should be noted that both Fortum Nuclear Services and UOP LLC A Honeywell have developed applications for mobile plants in cooperation with Graver Technologies Inc. (Selion license) and CNE Paks, respectively Toshiba, Shaw, and AVANTech Inc. (Columbia, S.C.).
In order to implement these products at Cernavoda NPP, an agreement is necessary to be signed between the beneficiary, the application developer and the materials manufacturer [6-10].

4. Conclusions

The maximum exchange capacity of the premix used at Cernavoda NPP for decontamination of aqueous radioactive waste is 0.85 meq NaCl/g product. Thus, starting from this value it was estimated that, under ideal conditions, the waste with a dissolved salt content of 25 mg/L is efficiently decontaminated using the full exchange capacity of the contacted Ecodex product.

Experimental tests have shown that, in the current configuration, the ion exchange filter belonging to the LRWS can ensure the decontamination provided in the technical specifications only if the waste has a dissolved salt content (TDS) below 10 mg/L.

Based on the obtained experimental results it was concluded that the improvement of this ion exchange filter can be done either by increasing the amount of adsorbent material used, while maintaining the treatment capacity, or by reducing the treatment capacity, while maintaining the amount of adsorbent material.

A calculation relationship has been established for estimating the actual waste volume that can be treated by 10 kg Ecodex, depending on the decontamination factor aimed.

At the ICN Pitesti, tests are being carried out to supplement the Ecodex premix, used at the Cernavoda NPP, with highly selective ion exchange materials, based on hexacyanoferates or containing salts of heteropolyacids.

R E F E R E N C E S

[1] "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management" Romanian National Report, Second Revision, August 2005.

[2] „Environmental Impact Assessment Report for Cernavoda NPP Units 3 and 4", The National Institute of Research and Development for Environmental Protection, ICIM Bucharest, Contract 203/2006.

[3] „Fisa de Prezentare si Declaratie" – revizia 0, Societatea Nationala Nuclearelectrica S.A., Sucursala CNE Cernavoda
[4] Memoriu de prezentare - Lucrări de construire a instalației de detritiere apă grea, Societatea Nationala Nuclearelectrica S.A., 2019
[5] "Powdex Selection Guide" – Graver Technologies, www.gravertech.com
[6] *Risto Koivula* "Inorganic ion exchangers for decontamination of radioactive wastes generated by the nuclear power plants", Report Series in Radiochemistry 23/2004, Helsinki 2003
[7] *Esko Tusa, Risto Harjula, Jukka Lehto* „Use of novel highly selective ion exchange media for minimizing the waste arising from different NPP and other liquids", Fortum Nuclear Services Ltd. and Laboratory of Radiochemistry, WM'03 Conference, February 23-27, 2003, Tucson
[8] *J. B. Pickett, W. E. Austin, H. H. Dukes* "Highly Selective Nuclide Removal From The R-Reactor Disassembly Basin At The SRS", Facilities Decontamination and Decommissioning Program Westinghouse Savannah River Co, Aiken, SC 29808, WM'02 Conference, February 24-28, 2002, Tucson, AZ
[9] *D.T. Bostick, S.M. Depaoli* „A comparative evaluation of IONSIV IE-911 and chabazite zeolite for the removal of radiostrontium and cesium from wastewater", B. Guo, Oak Ridge National Laboratory–Chemical Technology Division, ORNL/CP-99431
[10] "Cleaning up wastewater from nuclear contamination in Japan" WE&T Magazine – Water Environment Federation, October 2012, vol. 24, No. 10