On the Creation of a Modern System for Handling Liquid Radioactive Waste at Nuclear Power Plants in Ukraine. Conditioning of Liquid Radioactive Waste

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Abstract. The paper discusses approaches to creating a technological system for incorporating liquid radioactive waste (LRW) into a solid matrix to produce a final product that meets disposal requirements. The prompt resolution of this issue will alleviate the problem of LRW accumulation at operating nuclear power plants in Ukraine [1], complete the cycle of handling liquid waste, and focus the industry's potential on searching for and implementing a modern complex for handling both liquid waste and radioactively contaminated waters in general.

Keywords: Cementation · Inclusion in a polymetallic matrix · Flexible technology · Analysis of foreign experience · Adopted decisions

1 Introduction

The conditioning of LRW must be considered in the context of a strategy to minimize radioactive waste (RAW) with increasing safety requirements. This, in turn, necessitates the updating of regulatory frameworks. For example, for reliable and efficient handling of operational RAW at nuclear power plants and to meet the safety requirements of the International Atomic Energy Agency (IAEA) in the field of RAW management in Ukraine, it is necessary to develop and approve criteria for accepting RAW at nuclear power plants for long-term storage/disposal [2]. It should be noted that currently, there are no formally documented requirements for hardened LRW in Ukraine. Therefore, to assess the quality indicators of compounds, it is necessary to use the standard adopted in Russia (GOST 51883-2002).

A fundamental issue in the technology of conditioning by cementation is the development of binders (creating a compound recipe). The Research Institute of Binding Materials of the Kyiv National University of Construction and Architecture (RIIBM) is successfully working on this problem.

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2 Foreign and Domestic Practice of LRW Conditioning

According to available foreign and domestic sources, when choosing a hardening method, most specialists today prefer cementation and vitrification (in general - inclusion in an inorganic matrix), primarily due to safety and economic considerations. It should also be noted that abroad, work has been carried out for over 30 years on the application of gypsum [3]. There is information that for cementation of boron-containing concentrate, 1 kg of sand, 0.8 kg of cement, and 0.07 kg of gypsum are added to it at pH 6.5–7 for every 1 kg of boric acid (the mixture hardens in 28 days, and the leachability for Cs137 is 2×10^{-3} g/(cm^2 day)).

Adding sodium silicate (liquid glass) to binders (gypsum, cement) improves almost all main indicators: strength, degree of filling, compatibility with the main components of waste, leachability.

To increase the degree of filling and reduce leachability, the practice of "dry" cementation has been introduced, where the water-to-cement ratio is reduced from 0.7 (usual) to 0.35–0.4 (the associated deterioration in the flowability of the cement paste is irrelevant when forming the solid product in transport containers). For a long time in global practice, reinforcing additives (zeolites; vermiculite; clays; silicon dioxide; diatoms for binding excess water; organic derivatives; formaldehyde to prevent the proliferation of bacteria causing gas formation) have been used to change the physicochemical properties of cements and improve their compatibility with waste.

Trends in hardening methods abroad can be seen from the brief overview provided below.

Conditioning of LRW occurs by mixing them with cement (cement solution), bitumen, or polymer (polystyrenes, formaldehyde resin, polyesters, epoxies, polyethylene) followed by hardening of the resulting mass. Various options for changing the compositions of the inorganic matrix and cements by adding various clays, polymeric materials, etc., have been proposed. The technological cycle includes the extraction of radionuclides from liquid waste with the localization of toxic concentrates in a minimal volume. Significant attention is paid to the removal of ballast (non-radioactive) salts, which in turn reduces material costs for cementation.

Comparison of Different Methods of Solidifying Medium-Level (MLW) and Low-Level (LLW) Waste: A comparison of different methods of solidifying medium-level (MLW) or low-level (LLW) waste shows that all three types of matrices (bitumen, cement, polymers) are monolithic without any free water remnants. Cement and polymers are stronger substances, with their strength determined at 300–600 and 2000 kg/cm^2, respectively. Polymers and bitumen are fire hazards (polymers are combustible and partially decompose in fire, bitumen melts and ignites, hence their widespread future use is doubtful) [3].

Choice of Equipment: Both stationary and mobile conditioning plants can be used at nuclear power plant sites. Previously, stationary plants were constructed at each site of foreign nuclear power plants. In some countries, the use of mobile plants for conditioning both LLW and MLW is becoming widespread. In the UK, BNFL Environmental Services has been operating the country's first mobile plant for solidifying MLW (Transportable ILW Solidification Plant - TILWSP) since 2003 [4]. TILWSP is designed to process sludges and spent ion-exchange resins. The plant includes operations not only for processing wet MLW but also for their subsequent packaging in standard containers. Wet MLW are placed in 3 m^3 drums, where they are dehydrated and cemented. After checking the quality of the hardened mass, waste is poured with cement solution and the drum is sealed. Using remote equipment, the drum with conditioned MLW is placed in shielded transport packaging and transported to a special site for MLW storage.

In France, conditioning of technological wastes and very low-level ion-exchange resins is carried out in steel drums. All other types of wastes are conditioned in reinforced concrete containers, which have an internal steel lining.

At nuclear power plant sites with PWR-900 and some with PWR-1300, there are stationary facilities for encapsulating filters and cementing sludges and concentrates from evaporation in reinforced concrete containers. Mobile plants are used for conditioning such wastes at other nuclear power plants due to their cost-effectiveness and simpler mode of operation.

Cementing of LLW and MLW in the coming decades will likely remain in many countries the simplest, cheapest, and sufficiently safe method of conditioning. The main advantages of cementation are: low-temperature process; well-proven technology; the cemented product is non-combustible and has good thermal stability, chemically and biochemically stable; all forms of waste can be included in the cement matrix. Cementation can achieve reliable effective immobilization of waste, reducing its loading in cement, but this increases the volume of final products. Moreover, using this method, the salts contained in the waste interfere with the main processes of cement hydration, leading to deterioration of the cemented product quality over time.

The company NUKEM GmbH (Germany) has been offering cementation plants with various mixing methods for many years. Among them, the most widespread in the company's deliveries since the mid-1990s is the highly efficient mixing method in the drum (High Performance In-Drum Mixer - HPIDM [5]). Examples of the company's product deliveries include:

Ukraine, Khmelnytskyi NPP (HNPP) - cementation plant with an inclined mixer for the Waste Processing Center;
China, Qinshan NPP, Institute of Atomic Energy, Jiangsu Nuclear Corporation, CIAE - cementation plant in a 200-L drum;
Slovak Republic, Jaslovské Bohunice NPP - cementation plant with an inclined mixer for the Waste Processing Center;
Russia, Balakovo NPP - cementation plant with an inclined mixer for the Waste Processing Center.

The HPIDM method is applicable in both stationary and mobile installations (DEWA., MOWA). Depending on the radiation level, contact and non-contact control of the plant is possible. In mobile DEWA plants, the cementation process is carried out directly in waste containers; cement is loaded in advance. There are no special requirements for waste; it can contain up to 25% boric acid and up to 35% dry material. The MOWA system has features and advantages of a compact plant, as the waste is transported and stored in 20-foot containers that meet ISO standards. The system has high waste throughput (possible use of drums of various sizes (100–400 l)) and various protections.

The MOWA plant can process concentrates, pulp, granulated resins with high specific activity. Technical data of MOWA: length 5700 mm, width 2220 mm, height 2180 mm; weight 22,000 kg. Throughput: pulp/concentrate - up to 10 m^3 per shift; resin - up to 2 m^3 per shift [5].

Improvement in Cement Matrix Composition: Research is being conducted to improve the composition of the cement matrix, including for the purpose of reducing the leaching of Cs137 and decreasing hydrogen generation due to the corrosion of aluminum contained in the cement. It has been established that the addition of lithium nitrate to cement reduces hydrogen formation by approximately tenfold, and the addition of zeolite (clinoptilolite) reduces the leaching rate of Cs137 by tenfold.

Advancements in Vitrification Technology: Although the vitrification process was initially developed for processing high-level waste (HLW), it is now used for conditioning LLW and MLW. Vitrification of LLW has the advantage in terms of waste minimization and is suitable for all LLW generated at nuclear power plants.

In the USA, operational and planned new industrial facilities for vitrification of LLW, as well as mixed waste, are in place. The feasibility of vitrifying mixed LLW, consisting of granulated activated carbon contaminated with chemical and radioactive elements, has been demonstrated. The throughput of the industrial facility launched by ATG in 2001 in Hanford is 158.5 kg/h.

AMEC Nuclear (UK) has developed the GeoMelt technology, which is considered one of the most effective solutions for stabilizing LLW before removal [6]. The GeoMelt process (vitrification directly in the container) results in the immobilization of radioactive contaminants and heavy metals and the destruction of other toxic pollutants, forming a strong glass-like product. The feasibility of this technology was confirmed by hot trials on an experimental scale. GeoMelt technology was chosen for vitrifying LLW in Hanford after processing and vitrifying all HLW and some LLW stored in 177 underground tanks in Hanford.

The Hanford Vitrification Plant, under construction in Hanford for vitrifying LLW (Hanford Vitrification Plant), is part of the Waste Treatment and Immobilization Plant (WTP), also known as the "VitPlant." The complex is intended for processing LRW stored in Hanford's underground tanks. The complex includes four sections - for preliminary waste processing, for vitrifying LLW and HLW, and an analytical laboratory. The total area of the complex will be 26.3 ha. The VitPlant complex is to be constructed by 2016 and operational by 2019. The total cost is estimated at $12.2 billion [7].

However, the vitrification process, using expensive melting equipment with complex gas venting systems, leads to the formation of secondary waste. Due to these drawbacks, research continues to identify new binding materials (matrices) for immobilizing LLW/MLW. In the USA, a low-temperature method for stabilizing salt-containing waste using phosphate ceramics is being developed. In this process, magnesium oxide reacts with potassium phosphate and waste salts, resulting in a dense monolith with low porosity, primarily consisting of magnesium and potassium phosphates.

In South Korea, the Ulchin Vitrification Facility (UVF) for vitrifying LLW/MLW in a cold crucible melter (CCM) was commissioned at the Ulchin NPP in 2007 [4]. LLW/MLW generated at Ulchin-1 and -II NPPs (four units) contain 26% liquid concentrates, 18% spent ion-exchange resins, 4% spent filters, and more than half mixed heterogeneous waste. A technology representing a single-stage combustion and vitrification process for LLW/MLW was used. Combining a melting furnace with a cold crucible and a plasma torch melter (PTM), it is possible to separately vitrify combustible waste and melt non-combustible waste. The capacities of the CCM and PTM melters at the facility are 300 kW and 500 kW, respectively [8].

In 2013, a technology for conditioning LRW developed at the Jaslovské Bohunice NPP (Slovakia), based on incorporating waste into the SIAL geopolymer matrix, was presented in Ukraine [9]. However, tests of the technology at the Chornobyl NPP did not provide sufficient grounds for its industrial implementation at Ukrainian NPPs. Further testing is planned.

A positive domestic contribution to solving the problem of conditioning LRW is the research conducted at the Khmelnytskyi NPP on the study of stages of solid compound formation during the curing of real cubic residue (CR) and salt melt (SM), and the analysis of the properties of the resulting solid compounds. The research showed that with the help of polymetallic sorbents, it is possible to obtain a solid product suitable for subsequent long-term storage and disposal. The work was not completed (data as of 2004).

3 Cementation

Developing specialized compound recipes that allow for the cementation of salt-saturated solutions to produce a product that meets regulatory requirements is the basis of the cementation technology. In the past, the salt saturation limit for cementation according to SPORO-85 was restricted to 200 g/l, as higher concentrations significantly worsened the quality indicators of the cement stone. Currently, technologies for cementing solutions with high salt content have been successfully tested (from 750 g/l at the Chornobyl NPP to 950 g/l at the Rostov NPP).

The compound recipe must ensure the necessary quality indicators of the cement stone for a storage period of 300 years. In Ukraine, there are still no formally documented requirements for cured LRW, which forces developers to rely on standards adopted in the Russian Federation [10]:

Leaching rate (for Cs), g/cm^2 day - not more than 10^{-3};
Mechanical strength (compressive strength limit), MPa (kg/cm^2) - at least 4.9 (50);
Frost resistance (at –40… + 40 °C), cycles - at least 30 (*);
Immersion resistance to prolonged submersion in water, days - 90 (*);
Radiation resistance at a dose, Gy - 106().
() - reduction in compressive strength limit after testing not more than 25%.

Let’s take a closer look at two quality indicators of the final product of conditioning: durability and leaching rate. Regarding the durability of the final product in terms of maintaining its strength properties, direct studies of artificial stone based on any of the known hydrational hardening binders, including alkaline binding systems, confirming their durability for at least 300 years, have not been conducted. The reason is that, for example, Portland cement has been known for less than 200 years (E. Chiliev, 1822; D. Aspdin, 1824), and alkaline binding systems for less than 60 years (V.D. Glukhovsky, 1957).

The durability of materials is determined by the interaction and mutual influence of different factors, the main ones being: operating conditions; features of structural solutions of constructions; leaching; internal corrosion; compatibility of materials in the composition; resistance to alternating freezing and thawing, abrasion and wear; the influence of the condition of the structure on its durability, etc.

However, there are a number of indirect indicators and signs that suggest that stone based on alkaline binding systems can provide the required operational characteristics for 300 and more years.

Currently, the science of cement is focused on ancient structures made from artificial mixtures, which included soda and potash as components. In the last century, an attempt was made to decipher the reasons for the exceptional durability of ancient concrete, and the mineralogical composition of the cement stone of several ancient structures preserved under the long-term influence of various aggressive factors was studied [11–13]:

Roman aqueduct (Caesarea) - groundwater, flowing water;
Roman wharf - fresh flowing water;
Harbor walls (Caesarea) - Mediterranean seawater;
Roman baths - hot water from mineral springs.
In the structure of ancient concretes, artificial neoformations were found, analogous to natural zeolites of the type Na2O(K2O) Al2O3. (2–4) SiO2 2H2O.

At the same time, numerous cases of rapid destruction of Portland cement concrete (after 30…50 years of operation), used for the restoration of ancient Roman structures, are known, while ancient concretes operating in similar climatic conditions continue to be used for more than 2000 years (Table 1).

Table 1. Chemical composition of ancient lime-pozzolanic cements.

Name of territory	Mass share of oxides,%				
Ancient Greece (350 years BC)	SiO_2	Al_2O_3	$K_2O + Na_2O$	$CaO + MgO$	CO_2
Syria (Tel-Ramad, 70 years BC)	18,0	4,30	1,44	45,9	13,1
Egypt (Pyramid of Khufu)	24,6	4,92	1,55	41,8	25,9
Ancient Rome (169…140 years BC)	3,10	0,50	0,20	52,6	41,4

The format of the article does not allow for a detailed description of alkaline binding systems. It should be noted that a significant contribution to the implementation of the technology for cementing liquid radioactive waste (LRW) has been made by the work of Ukrainian scientists. For instance, the Research Institute of Binding Materials, in the framework of developing the D-2 package for the LRW Processing Plant strategy and considering the requirements [10, 14], conducted several studies to determine: the radioactive properties of the final product with real LRW; the influence of alkaline cements from various manufacturers on the recipes for solution mixes and the characteristics of the final product; the influence of kaolin on the solution mix recipe and properties of the final product; durability (analytical assessment) of the final product in terms of maintaining strength properties; compliance of the final product's characteristics with the requirements stated in the criteria for acceptance in specially equipped near-surface storage of solid radioactive waste (NSSRW), as well as in technical specifications.

The reliability of radionuclide binding is ensured by the fact that many radionuclides (primarily alkaline and alkaline earth types such as cesium, strontium, sodium, potassium) are chemically capable of entering the structure of zeolite-like neoformations and are firmly fixed in them. Other non-alkaline radionuclides can be reliably physically bound by the zeolites of slag-alkaline cement stone, which have sorption properties [11].

Evidence of the high efficiency of using alkaline cements as a binding material for immobilizing LRW can be seen in the fact that such natural zeolites as analcime, chabazite, sodalite, natrolite, clinoptilolite, mordenite, etc., which also occur in the formation of the stone structure on alkaline cements, are capable of cation exchange of sodium and potassium for cesium, and calcium for strontium. These data confirm the increased reliability of radionuclide localization in the matrix of artificial stone based on alkaline cements, and the high sorption properties of zeolite-like neoformations synthesized in alkaline cement stone serve as an additional factor of reliability for radionuclide binding. It should be noted that regardless of the directionality and scale of the technological process of using alkaline cements, the formation of properties of artificial stone will be accompanied by the synthesis of the above-mentioned structural formations, ensuring high density of the stone and stability of structural compounds under leaching conditions.

In the research, products from domestic manufacturers were used as binding materials: cement LCEM I-400 according to DSTU B V.2.7-187:2009 produced by CP "Ekosplav", and as additives - plasticizer "Poliplast SP-3" according to TU 5870-006-58042865-05, kaolin from LLC "Prosyansky GOK" grade KR-2 according to GOST 19608-84, and Portland cement PC I-500 (DSTU B V.2.7-46-96) by LLC "Volyn-Cement" (Zdolbunov). To determine the influence of the qualitative characteristics of the cement component on the characteristics of solution mixes and the characteristics of the cured final product, cements LCEM I-400 according to DSTU B V.2.7-187:2009 from other manufacturers were additionally used, namely slag cement by CP "Golden Technologies Company" and cement produced by LLC "Promcement". As materials included in the composition of slag-alkaline cements, granulated blast furnace slags from the Zaporizhzhia metallurgical combine (ground product producer CP "Golden Technologies Company"), Mariupol metallurgical combine named after Ilyich, and Kryvyi Rih combine "Arcelor Mittal Kryvyi Rih" were considered.

4 On the Choice of Technology for Operating Nuclear Power Plants in Ukraine

As noted in the work [1], for the prompt solution of the problem of conditioning LRW at Ukraine's nuclear power plants, experts from the Scientific and Technical Center of NAEK Energoatom chose cementation. The technology of cementation has been mastered in the Russian Federation at the Rostov NPP (VVER) where a curing installation (UI) is in operation, and in Ukraine at the Chornobyl NPP LRW Processing Plant (RBMK).

The developer of the comprehensive technology of cementation for the Rostov NPP is the Open Joint Stock Company "Sverdlovsk Research Institute of Chemical Engineering" (OJSC SVNIKhM) [15]. The UI has been in pilot-industrial operation since 2005 and currently performs operations for cementing only cubic residues (CR). During the implementation of the project, the personnel identified several shortcomings in the project, which were eliminated during the commissioning and testing phase. It was also necessary to work out the mixture recipe to bring the processing product in line with the requirements of the current nuclear power guideline in Russia, RD 95 10497-93 ("Guidelines for the Quality of Compounds Formed During Cementation"). VNIINM, SVNIKhM, ZAO NPO "Energochimproject", and NPO "Radon" participated in the development of the compound recipe. The matrix is a cement-clay mixture (a mix of bentonite and Portland cement brand M500 (PC 1-500) of Russian manufacturers in a ratio of 1:9). The cement compound recipe: CR concentrate – 38%; PC + bentonite – 59%; NaOH solution (46%) – 3%. Since 2011, after the modernization of the installation, they switched from barrel to container storage of cured waste (containers NZK-150-1.5P), which simplified and reduced the cost of the technological process.

The technological process is structured as follows: concentration of CR; preparation of the cement mix with technological additives (CMTA); mixing of concentrated CR (CCR) with CMTA; packaging of the cement compound in NZK container; transportation of containers to the sedimentation tank; transportation of containers after sedimentation to the TRW storage of the special-purpose building (TRW SPB).

The installation consists of four main technological units: reception, preparation and dosing of LRW; reception, preparation and dosing of cement; mixing; packaging with a transport system.

The decision to use the experience of the Rostov NPP in Ukraine is complicated by the absence of a document confirming that the final product meets all the requirements of GOST 51883-2002 and there is no cost calculation for conditioning and storage of the final product.

The Chornobyl NPP LRW Processing Plant (ZPLRW) is Ukraine's first experience in solving the problem of creating technology for the final stage of handling liquid waste. The cementation technology for ZPLRW was created by a domestic developer - NIIVM. The technology uses the following materials and reagents: cements LCEM 1-400 and PC-500, plasticizer SP-3, special-purpose additives (calcium nitrate), thinning additives (Pozzolith 400 N), additives (PPFeNi), NAOH, HNO3.

The functions of ZPLRW include: extraction of waste from storage tanks by pumping and mixing; transportation of extracted waste to reception tanks with partial use of existing pipelines; preliminary processing of waste to bring their characteristics in line with the requirements of subsequent stages of the technological process; volume reduction: centrifuging of resins and perlites (to adjust the moisture content of the waste) and further evaporation of CR; processing and cementation of LRW; packaging of the final product in barrels; retention of barrels with the final product; packaging of barrels in transport packaging sets (TPS) in groups of four barrels; removal of filled TPS.

The plant is designed to process 2500 m^3/year of waste stored in 14 tanks, with an operational life of 10 years. It should also be noted that the permission for the acceptance of RAW from ZPLRW to the NSSRW is temporary, as are the acceptance criteria. Out of 22 sections of the storage, only two are permitted for reception (storage volume 71280 m^3).

The technology of ZPLRW is oriented towards conditioning complex composition waste. The specifics of LRW are due to both the waste of the Chornobyl NPP and the inflows from the Shelter object (the waste contains transuranic elements, a large amount of sulfates, phosphates, oxalates, as well as petroleum products, synthetic surfactants, film-forming materials, and organic substances) [16].

Unlike VVER NPPs, LRW from RBMK NPPs does not contain boric acid, and heterogeneous waste contains perlites, which have high abrasive properties. The presence of abrasives negatively affects the resource of the moving elements of the mixer (noted by the plant personnel).

From a technical point of view, the processes of cementation at the UI of the Rostov NPP and at the ZPLRW of Chornobyl NPP are fundamentally identical.

5 Comparative Assessment

Let's focus on issues important for deciding on the choice of cementation technology and the LRW handling production system for Ukrainian NPPs.

The Chornobyl NPP ZPLRW and the UI of the Rostov NPP are production systems with different levels and scales of implementation, different technical and strategic tasks (with the same tactical task).

Overall, the technology of ZPLRW is on the scale of a plant, and the technology of the Rostov NPP is on the scale of a workshop.

Regardless of the large volume of waste accumulated at the Chornobyl NPP and the volume of their inflows in the process of liquidating the object and transforming the NPP zone into an environmentally clean system, it has a finite size. According to the developer's assessment, this is 13,481.5 m^3 of CR, 4,059.7 m^3 of ion-exchange resin pulp, and 2,272.18 m^3 of filter perlite pulp. These wastes are stored in LRW and LRWTO. SP is absent. ZPLRW performs, practically, a one-time task.

On operating facilities, LRW is generated and arrives continuously, and therefore the life of the LRW conditioning system should be no less than the life cycle of the station. Based on this, it is important to assess the productivity of the technology, based on the dynamics of LRW accumulation (on the principle of reasonable sufficiency).

At ZPLRW, the finished product is sent for disposal outside the NPP within the boundaries of the Chornobyl exclusion zone. At the Rostov NPP, long-term storage is carried out at the station's industrial site.

At the Chornobyl NPP LRW Processing Plant (ZPLRW), the drum packaging principle of the processed product is implemented, with subsequent use of Transport Packaging Sets (TPS) as returnable, reusable packaging. At the Rostov NPP, a container packaging principle is laid down, in which containers (NZK) are not returned.

The Chornobyl NPP ZPLRW, whose creation stretched over 15 years, does not yet have sufficient operational statistics, which are available at the Rostov NPP.

The economic aspect is of great importance. At ZPLRW, its specialists performed an "Economic calculation of operational costs for processing LRW for one year, taking into account technological means, electricity, and labor fund, including disposal in the

Near-Surface Waste Disposal Facility (NSSWDF), as well as the calculation of the cost of processing 1 m^3 of LRW for one year" (by L.A. Gladneva). Based on the calculation at 2012 prices:

Cost of disposal (according to the letter of the State Specialized Enterprise "Centralized LRW Management Company" № 105/1509 dated 28.12.2011) at the first stage of the "Vector" complex (NSSWDF) - 10,300 UAH/m^3;
Cost of processing 1 m^3 of CR - 73,973.2 UAH/m^3;
Cost of processing 1 m^3 of ion-exchange resins - 139,846.8 UAH/m^3;
When co-disposing homogeneous and heterogeneous waste in a cement matrix, the average price is 68,000 UAH/m^3. Note that cementation of LRW (ion-exchange resins) in Slovakia costs 32,567 euros/m^3, and disposal – 112,000 euros/m^3 (data from 2013, including the prices for disposal in the National RAW Repository).

With the design capacity of ZPLRW of 632.1 m^3 of CR per year (2100 m^3 of final product), their conditioning and storage per year will cost 46,758,870.98 UAH. The same for heterogeneous waste (ion-exchange resins) with the plant's design productivity of 322.1 m^3 per year (2102 m^3 of final product) will cost 45,044,654.22 UAH.

The Rostov NPP does not provide such calculations.

6 Conclusion

As noted, the priority direction for the prompt solution of the problem of conditioning LRW by the Scientific and Technical Center of NAEK Energoatom has been chosen to be cementation [1]. In terms of creating a modern system for handling LRW at operating NPPs in Ukraine, a number of requirements are presented for the cementation system:

Implementation level taking into account the reduction of cementation scale as the complex for handling LRW is introduced and technological processes are automated. The levels of implementation can be: the level of a technological line, the level of a site, the level of a workshop, and the level of a plant. It is necessary to seek an optimal way of solving the problem, possibly at a lower level.

1. Strategic flexibility. This means that the equipment should provide work with other matrix materials (for example, geopolymers).
2. Tactical flexibility, allowing various options of technological processes to be tested during pilot-industrial operation.
3. Adaptability to the skill level of the facility's staff.
4. Mobility of some technical means, their unification in terms of the prospective task of creating a flexible mobile technology.
5. Maximum use of standardized equipment.

Cementation is a real way to solve the problem of LRW of domestic NPPs today. At the same time, it is necessary to continue searching for more efficient matrix materials. The high cost of conditioning and disposal should stimulate work to reduce the volume of waste. The task of the next stage is the deep processing of CR [9].

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