

Low-temperature resistance and cryodestruction of ion-exchange resins used in uranium sorption

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Abstract: This study investigates the low-temperature resistance and cryodestruction behavior of ion-exchange resins used in uranium sorption. Eight commercial resins, including AMP, BO-020, Purolite A-606, BD-706, Tulsion 3663, Amberlite IRA-120, Resinacs, and Dowex-1, were evaluated using granulometric, mechanical, and structural characteristics. Particular attention was given to AMP, BO-020, and A-606 before and after freezing. The results showed that freezing reduced mechanical strength and mean particle diameter, indicating damage to the polymer matrix. The degree of destruction was strongly associated with particle size: particles smaller than 0.3 mm were comparatively stable, whereas fractions of 0.3–0.8 mm and above 0.8 mm were increasingly susceptible to cracking and fragmentation. Moisture content and pore structure also influenced freeze-induced degradation. Repeated freeze–thaw cycles caused a shift toward smaller particle fractions and changes in resin structure. The findings provide a basis for selecting and operating ion-exchange materials under low-temperature conditions in uranium recovery and related technological processes.

Keywords: ion-exchange resins; uranium sorption; cryodestruction; low-temperature resistance; particle size; freeze–thaw cycles.

INTRODUCTION

Uranium is an important strategic resource widely used in the nuclear energy sector, and the efficiency of its extraction largely depends on the development of effective, economically viable, and environmentally acceptable hydrometallurgical technologies. In modern uranium production, in-situ leaching is one of the important methods for extracting uranium from suitable deposits. This technology involves the circulation of leaching solutions through ore-bearing formations followed by the recovery of uranium from the resulting productive solutions [7]. Among the available methods for treating uranium-bearing solutions, ion-exchange sorption is of particular importance because of its technical and economic advantages and its relatively low environmental impact. According to the reviewed research, uranium in sulfuric acid solutions predominantly occurs in the form of complex uranyl sulfate anions, which makes strong-base anion-exchange resins suitable for its recovery from productive solutions [3].

The efficiency of uranium sorption is strongly dependent on the physicochemical and technological properties of the ion-exchange resin. These properties include particle-size distribution, mechanical strength, sorption capacity, selectivity, regeneration characteristics, porosity, swelling behavior, and resistance to chemical and environmental influences. Since there is no universal ion-exchange resin suitable for all technological conditions, the selection and evaluation of sorbents

according to the specific characteristics of the uranium-processing system remain important scientific and technological tasks [14]. In particular, the mechanical stability, selectivity, regeneration ability, granulometric composition, and behavior of ion-exchange resins under low-temperature conditions require detailed investigation [9].

Low-temperature exposure represents a particularly important problem in the practical use, transportation, and storage of synthetic ion-exchange resins. Water contained within the porous structure of resin granules undergoes significant changes during freezing. The formation of ice crystals can simultaneously cause local compaction of the granules and an increase in the volume of their internal contents. These opposing processes generate mechanical stresses within the polymer matrix and may result in cracking, deformation, and irreversible structural damage, commonly referred to as cryodestruction [2]. Consequently, repeated or prolonged exposure to negative temperatures can alter the structural integrity and technological performance of ion-exchange resins.

The problem becomes particularly relevant for uranium-processing operations conducted under seasonal climatic conditions where technological materials may be exposed to negative temperatures. Previous studies cited in the dissertation have investigated different approaches to improving uranium sorption, including the use of modified ion-exchange materials, ultrasound-assisted sorption, and the effect of low temperatures on ion-exchange processes. However, the dissertation emphasizes the need to evaluate ion-exchange resins under temperature conditions characteristic of the regional climate. In particular, the study considers the behavior of resins at winter temperatures reaching approximately $-18\text{ }^{\circ}\text{C}$ and examines the changes occurring in different resin fractions under these conditions [10].

An important aspect of this problem is the relationship between resin particle size and resistance to low-temperature exposure. The experimental observations reported in the dissertation indicate that resin fractions smaller than 0.3 mm demonstrate comparatively greater stability and tend to preserve their shape during periods of low winter temperatures. Resin particles in the range of 0.3–0.8 mm may undergo cracking and fragmentation, whereas particles larger than 0.8 mm can experience more pronounced breakage and structural damage [5]. These observations demonstrate that particle-size distribution should be considered together with mechanical strength and other physicochemical characteristics when selecting ion-exchange resins for uranium sorption processes under seasonal low-temperature conditions [8].

Therefore, the systematic evaluation of ion-exchange resins according to their physicochemical, mechanical, and technological characteristics is necessary for improving the reliability of uranium recovery from productive solutions. The present study focuses on the investigation and selection of ion-exchange resins used in uranium in-situ leaching and processing technologies, with particular attention to their granulometric composition, mechanical strength, uranium sorption capacity,

regeneration degree, residual exchange capacity, and resistance to negative temperatures [11]. The study also aims to identify suitable ion-exchange materials and technological conditions that can reduce resin degradation and maintain effective uranium recovery during seasonal periods of low temperature.

RESEARCH METHODOLOGY

The study evaluated the low-temperature resistance of ion-exchange resins used in uranium sorption processes. The investigated materials included AMP, BO-020, Purolite A-606, BD-706, Tulsion 3663, Amberlite IRA-120, Resinacs, and Dowex-1. Representative resin samples were prepared by sample reduction and analyzed for granulometric composition using wet and dry sieve methods. Mechanical strength was determined before and after mechanical treatment, while the effect of negative temperature was assessed by comparing the condition of resin granules before and after freezing.

For the low-temperature experiment, particular attention was given to A-606, AMP, and BO-020 resins. Changes in mechanical strength and mean particle diameter after freezing were used as the principal indicators of cryogenic degradation. In addition, the resins were divided into three particle-size ranges (<0.3 mm, 0.3–0.8 mm, and >0.8 mm) to evaluate the relationship between particle size and resistance to freezing.

Table 1. Experimental parameters used for evaluation of ion-exchange resins

Parameter	Experimental approach
Ion-exchange resins	AMP, BO-020, A-606, BD-706, Tulsion 3663, Amberlite IRA-120, Resinacs, Dowex-1
Granulometric composition	Wet and dry sieve analysis
Particle-size fractions	<0.3 mm; 0.3–0.8 mm; >0.8 mm
Mechanical strength	Comparison before and after mechanical treatment
Low-temperature resistance	Comparison of resin condition before and after freezing
Main indicators	Mechanical strength and mean particle diameter
Additional quality parameters	Specific surface area, density, selectivity, and regeneration characteristics

The methodology enabled the effect of freezing on the structural and mechanical stability of ion-exchange resins to be evaluated and provided a basis for comparing their suitability for uranium sorption under seasonal low-temperature conditions.

RESULTS

The experimental results demonstrated that low-temperature exposure caused measurable changes in the mechanical strength and granulometric characteristics of the investigated ion-exchange resins. The most pronounced changes were observed for A-606, AMP, and BO-020. After freezing, the mechanical strength of the resin granules decreased, while their mean particle diameter was also reduced. These changes indicate that freezing and subsequent thawing can lead to structural damage of the polymer matrix.

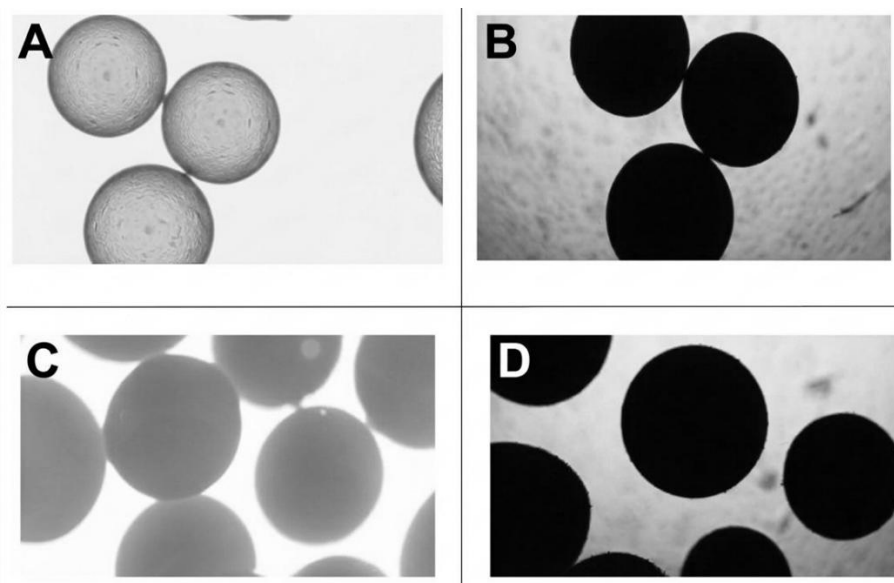


Figure 1. Microscopic appearance of BO-020 ion-exchange resin before and after low-temperature exposure.

A - Unfrozen BO-020 ion-exchange resin; B - Frozen BO-020 ion-exchange resin; C - Uranium-loaded BO-020 before freezing; D - Uranium-loaded BO-020 after freezing at -18.2°C .

The visual observations confirmed the occurrence of structural changes after cooling. The dissertation data show that BO-020 resin was examined before and after freezing using a binocular digital microscope. Repeated freezing caused a shift of the granulometric composition toward smaller fractions, indicating a decrease in the average particle diameter. For A-606 and AMP, visible defects were also observed, while AMP particles exhibited a particularly pronounced degree of destruction.

The quantitative results of the freezing experiments are presented in Table 2. The mechanical strength of A-606, AMP, and BO-020 decreased after freezing. For example, BO-020 samples initially showed mechanical strength values of up to 100%, whereas after freezing the corresponding values decreased to approximately 83.5–85.0%. Similar reductions were observed for A-606 and AMP. The mean particle diameter also decreased after freezing in the investigated samples.

Table 2. Changes in selected ion-exchange resins after freezing

Ion-exchange resin	Sample	Mechanical strength before freezing, %	Mechanical strength after freezing, %	Mean particle diameter before freezing, mm	Mean particle diameter after freezing, mm
A-606	I	99.5	81.0	0.85	0.40
A-606	II	97.5	77.0	0.75	—
A-606	III	92.0	83.0	0.65	—
A-606	IV	97.5	—	0.60	—
A-606	V	84.0	—	0.70	—
AMP	I	99.5	76.5	0.85	0.30
AMP	II	98.0	73.0	0.65	—
AMP	III	90.5	78.0	0.55	—
AMP	IV	98.0	—	0.45	—
AMP	V	81.5	—	0.60	—
BO-020	I	100.0	83.5	0.95	0.75
BO-020	II	99.0	81.0	0.85	—
BO-020	III	98.0	85.0	0.75	—
BO-020	IV	99.5	—	0.70	—
BO-020	V	86.5	—	0.80	—

The results also demonstrated a clear relationship between particle size and resistance to low temperatures. Particles smaller than 0.3 mm were comparatively stable and retained their shape, whereas particles in the range of 0.3–0.8 mm showed cracking and partial breakage. Particles larger than 0.8 mm were more susceptible to cracking and destruction. Thus, larger granules were more strongly affected by the mechanical stresses generated during freezing.

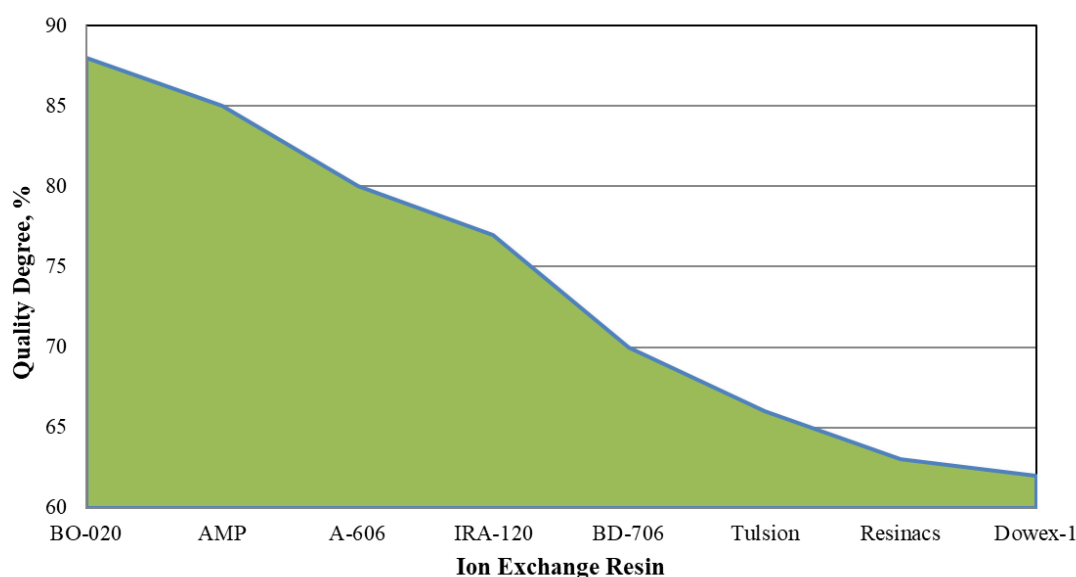


Figure 2. Quality characteristics of the investigated ion-exchange resins.

The overall quality assessment also showed differences among the investigated resins based on granulometric composition, mechanical strength, specific surface area, density, selectivity, and regeneration characteristics. The corresponding quality values were reported as 88% for BO-020, 85% for AMP, 80% for A-606, 77% for Amberlite IRA-120, 70% for BD-706, 66% for Tulsion, 63% for Resinacs, and 62% for Dowex-1.

Finally, the results indicated that the duration of a single freezing exposure had a relatively limited effect on the cryodestruction process. Polymer-type ion-exchange materials maintained their

exchange capacity during storage at temperatures from 0 to $-50\text{ }^{\circ}\text{C}$ for several months, whereas polycondensation-type resins showed a decrease in exchange capacity of up to approximately 15% after six months. The higher resistance of polymerized sorbents was associated in the source with their more developed spatial polymer structure.

CONCLUSION

The results demonstrate that low-temperature exposure significantly affects the structural integrity of ion-exchange resins used in uranium sorption. Freezing caused a decrease in mechanical strength and a reduction in mean particle diameter, indicating cryodestruction of the resin granules. The extent of damage depended strongly on the initial particle size and structural condition of the resin. Particles smaller than 0.3 mm showed comparatively higher resistance, whereas larger particles, particularly those above 0.8 mm, were more susceptible to cracking and fragmentation. Among the investigated materials, A-606, AMP, and BO-020 showed measurable changes after freezing, with AMP particles exhibiting the most pronounced structural damage.

The study also indicates that the duration of a single freezing exposure has a relatively limited effect on cryodestruction, while resin moisture content and pore structure play an important role in freeze-induced damage. Polymer-type ion-exchange materials generally retained their ion-exchange capacity during storage at temperatures from 0 to $-50\text{ }^{\circ}\text{C}$ for several months, whereas polycondensation resins could experience a decrease in exchange capacity of up to 15% after six months. Therefore, the selection of ion-exchange resins for uranium recovery under low-temperature conditions should consider mechanical strength, particle-size distribution, moisture content, porosity, and structural stability to ensure reliable operation and minimize degradation during freeze–thaw cycles.

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