USING HOT ISOSTATIC PRESSING FOR RADIOACTIVE WASTE ISOLATION PURPOSES

Pokhitonov Yu. A.[1], Starchenko V. A.[1], Dalyaev I. Yu.[2], Titov S. L.[3]

[1]**JSC V. G. Khlopin Radium Institute, St. Petersburg, Russia**

[2]**Federal State Autonomous Scientific Institution Central Research and Development Institute of Robotics and Technical Cybernetics, St. Petersburg, Russia**

[3]**LLC Design Institute Petrohim–Technology, St. Petersburg, Russia**

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The paper summarizes the findings of a study focused on hot isostatic pressing (HIP) technique implemented by the Khlopin Radium institute. The equipment was designed and manufactured at the Kharkov's Physics and Technology Institute. The installation provided a pressure of up to 400 NPa with the pressing temperature of up to 1 250 °C. The experiments were carried out on installations located in hot cells in the radiochemical department (Gatchina city). Samples of materials for HLW immobilization (titanate ceramics of the synroc type, stabilized cubic zirconia) and matrices for ^{129}I immobilization based on copper iodide and metallic copper were obtained. The leaching rate of HLW elements (simulators) from these samples amounted to $(0,5–1,5)\cdot10^{-9}$ g/(cm^2·day). Despite high-performance characteristics of the materials obtained, some problems were revealed associated with the remote maintenance of equipment and the lack of industrial design analogues. Considering the experience gained, we believe that fairly simple equipment can be designed implying no complex systems and providing minimum preparatory operations. Joint efforts of technologists and designers will enable the automatization of equipment management and control through local control systems. Material loading and unloading operations can be robotized as well. Such technical solutions are expected to be in demand at industrial facilities for HLW final disposal (or when handling damaged fuel during the decommissioning of radiation and nuclear hazardous facilities).

Keywords: *radioactive waste, hot isostatic pressing, liquid radioactive waste, calcination, crystalline mineral-like matrices, plasma chemistry, solid-phase synthesis.*

When eyewitnesses are silent, legends are born.
I. Ehrenburg

Introduction

From an environmental point of view, any nuclear power generation technology is characterized by a major inherent drawback, which is waste accumulation requiring costly management and disposal operations. For this reason, the energy sector has been evolving in parallel with the advancement of waste processing methods. Large-scale research on the immobilization of radionuclides were started with some studies focused on the vitrification of liquid waste [1, 2] and the synthesis of ceramic materials — analogues of stable natural compounds (Synroc) [3]. The first composition proposed by Ringwood in 1978 was the Synroc-A composition formed by waste melting at a temperature of about 1 300 °C [4]. The higher chemical and radiation resistance of mineral-like materials and the opportunities for their property assessment based on their comparison with natural analogs helped to predict

their long-term behavior, i. e., assuming a time period required for the bulk of long-lived radionuclides to decay.

It should be noted that all these years, research on the synthesis of mineral-like materials for HLW immobilization purposes was performed in parallel with the structure improvement of the extraction flowchart and the fractionation technology being viewed as an integral part of the Purex process. It was believed that irradiated fuel reprocessing at radiochemical plants and the use of fractionation technology in combination with subsequent synthesis of mineral-like materials would provide maximum safety during further storage and disposal of all long-lived radionuclides contained in them.

Hot isostatic pressing (HIP) method was basically deemed as a most promising method providing the generation of ceramic products containing HLW components [5—8]. In 1980's — 1990's, the Radium Institute implemented a large research program focused on the solid-phase synthesis based on the HIP method. In parallel, studied were the HLW denitration methods and the production of matrix material powders by plasma-chemical method. At that time, the Radium Institute also paid much attention to the challenge of iodine-129 immobilization.

All these studies was implemented in close collaboration with the Kharkov Institute of Physics and Technology, where the GAUS-4/125035 unit was designed and manufactured providing a maximum working pressure of 400 MPa and a pressing temperature of up to 1 250 °C [5—8]. Relevant findings were planned to be used at the RT-2 plant. The reasons behind the decision on the termination of these research, as well as the shutdown of many other important programs in radiochemistry, need no comment.

This article overviews the studies performed by the Radium Institute and evaluates the prospects for further application of the HIP method.

Experimental part and discussion of results obtained

The studies implemented by the Radium Institute were mainly focused on the development of ceramic matrices for HLW immobilization and of a relevant technology involving a number of operations (Figure 1).

Along with high temperature and pressure, the preparation of the starting reagents plays an important role in the synthesis of ceramic materials. It requires that all components are thoroughly mixed at a submicron level prior to the high-temperature processing [9].

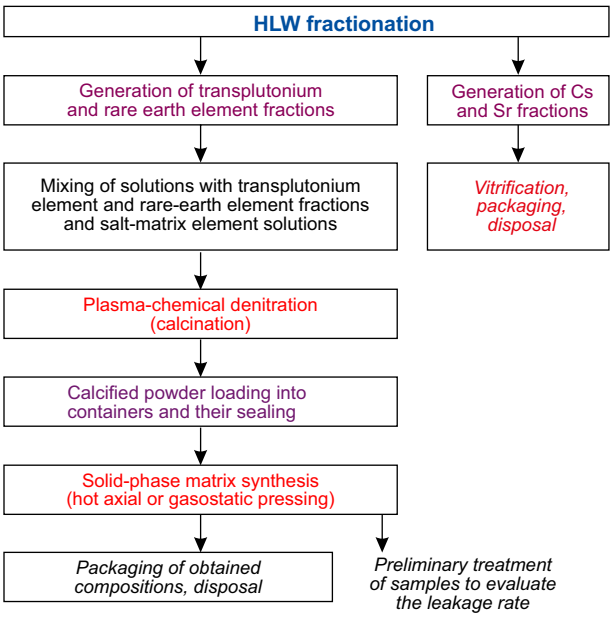

Figure 1. HLW immobilization process flowchart

Prior to proceeding with the pressing results, let's take a closer look on the synthesis of powders - the initial matrix components. Many studies showed that mechanical mixing of individual components, even assuming their sufficiently fine grinding, not always resulted in a desired product (it was not possible to obtain a homogeneous mixture of powders with a high degree of dispersion).

Plasma-chemical process was deemed as a most optimal method out of all denitration methods known at that time. This method provides very fine powders (0.03—0.10 μm) for further solid-phase synthesis and, at the same time, a high degree of homogeneity of the resulting oxides. To address this problem, the All-Russian Research Institute of High Frequency Currents named after V. P. Vologdin developed a plasmatron with a split water-cooled stainless-steel chamber. The characteristics of the induction high-frequency generator were as follows: voltage — 380 V, rated power — 60 kW, oscillatory power — 40 kW, operating frequency — 1.76 ± 0.44 MHz.

The flow rate of the plasma-forming gas (argon, nitrogen, air) was ranging from 30 to 300 l/min, the working pressure amounted to 90 kPa, the pressure of the cooling water was 0.2 MPa and the feed rate of solutions flowing into the plasma-chemical reactor was up to 20 l/h.

The plasma process was initiated in a flow of argon, which was then replaced by air. Flame cone of the reactor and spray nozzles were designed and manufactured at the Leningrad Research and Production Association named after V. Ya. Klimov (now JSC Klimov).

The installation was warmed up first and then the initial solution was supplied to the distribution device, where it was dispersed under high pressure through nozzles into plasma-chemical reactor. In the reactor, the solution evaporated and the dried salt residue decomposed into oxides in about 0.1 s. The temperature of the steam-dust-gas mixture flowing out of the reactor was about 700—900 °C. The resulting oxide powders were collected in two cyclones (vortex precipitators) arranged in series. The steam-gas mixture was supplied to the gas treatment system through a condenser-heat exchanger and then fed to the ventilation system of the building. After cyclones cooling, the oxide powders were extracted for subsequent synthesis of matrices and further research.

Plasma-chemical denitration was implemented both to generate matrix material powders required for subsequent synthesis (for example, zirconium and aluminum oxides) and element oxides simulating HLW composition (cesium, europium and gadolinium oxides). The latter were generated in the form of individual compounds or as a mixture containing oxides of inorganic matrix materials (IMM). Nitric acid solutions of salts were used as initial solutions for plasma-chemical denitration. Concentration of nitric acid was 2—3 M, whereas the concentration of salts varied within a range of 50—150 g/L [9]. The obtained oxide powders were analyzed using the X-ray phase method, laser granulometry and electron microscopy. In all cases, complete transition of nitrates to corresponding oxides was observed. A somewhat different picture resulted from the X-ray phase analysis of the products obtained by denitration of nitrate mixtures. This study showed that already at the plasma-chemical calcination stage, partial synthesis of the specified components or their intermediates could be observed, which, obviously, greatly facilitated the conditions for subsequent solid-phase synthesis.

Granulometric analysis of obtained powders was implemented. It was demonstrated that under most of the experiments performed, the particle size in the second cyclone-precipitator did not exceed 1 μm. Whereas, in the first one it did not exceed 5 μm. These values were obtained for both individual oxides and their mixtures. Using a scanning electron microscope, photographs of the particles generated from the plasma-chemical treatment were taken. Most of them were spherical, and, depending on the conditions, their number varied from 70 to 95 %.

In case of hot axial pressing, a twenty-ton hydraulic press equipped with a gas-tight chamber was used. Pressing was done for 1 hour in argon atmosphere in a graphite matrix at a temperature of 1 000—1 200 ° C and a pressure of 20—30 MPa.

The gas-static pressing equipment was manufactured at the Kharkov Institute of Physics and Technology (NSC KIPT) under a joint research program with the Radium Institute (Figure 2). The structure of such installations basically involves a gas-stat and a gas compressor. The gasostat was a metal cylinder fitted with upper and lower plugs. It had a chamber inside with a resistance furnace. Pressing temperature amounted to 1 000—1 200 °C, pressure varied in the range of 350—400 MPa, pressing time accounted for 2 hours. The pressure in the gasostat was generated by a cryogenic thermal compressor. It should be noted that this unit specifically applies a KRIT-type compressor developed by the NSC KIPT with its operation principle based on sequential cooling and heating of the working gas (argon) [5, 6].

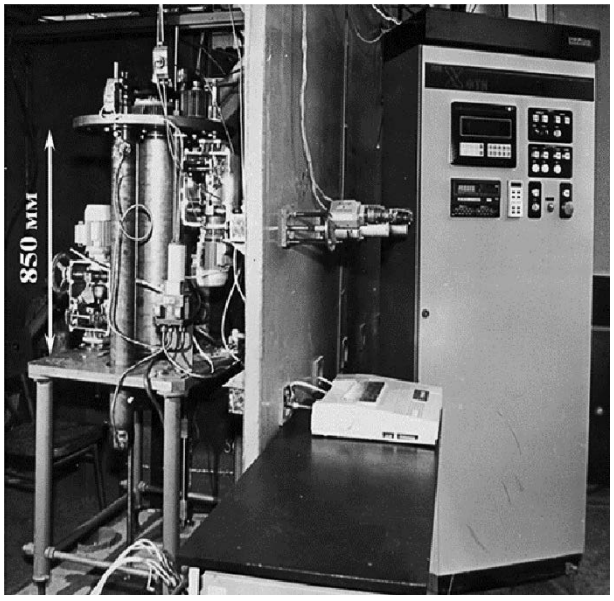

Figure. 2. External view of the laboratory GAUS 4/1250 35 HUI unit [6]

Samples of titanate ceramics similar in their composition to Synroc were produced by this unit. A mixture of plasma-chemical powders of inorganic matrix materials and simulators of fission products was used as initial composition for solid-phase synthesis. Only titanium dioxide was not produced in the plasmatron and was introduced as a separate additive in the form of pigment titanium dioxide.

Table 1 summarizes the synthesis conditions and some characteristics of the obtained products.

X-ray phase analysis of the samples showed the presence of the following main phases: zirconolite ($CaZrTi_2O_7$), hollandite ($BaAlTi_5O_{14}$, rhombic), perovskite and rutile in various ratios. Depending

Table 1. Conditions for solid-phase synthesis and characteristics of mineral-like compositions based on titanate ceramics and cubic zirconia (stabilizer – Y_2O_3)

Conditions of the experiment				Characteristics of the obtained samples	
Temperature, °C	Pressure, MPa	Pressing time, min	HLW simulator	Density, g/cm³	Porosity, %
1000	450	120	CeO_2	4.6	0.5
1100	20	60	CeO_2	4.5	0.5
1200	25	60	CeO_2	4.6	0
1200	30	60	CeO_2	4.6	0
1200	20	60	UO_2	4.9	0
1000	350	120	UO_2	4.6	–
1200	30	60	UO_2	4.6	27.0
1200	30	60	Eu_2O_3	4.0	22.0
1350	65	60	Eu_2O_3	5.1	12–14
1500	150	120	UO_2	5.7	3–5
1450	400	120	UO_2	5.89	–

on the experimental conditions, the perovskite content varied from 20 to 60%, zirconolite — from 10 to 30%, hollandite — from 7 to 20%, and rutile — from 10 to 30%. In this case, fission product simulators did not form their own phases and constituted to the crystal lattice of the matrix compounds.

X-ray study of the obtained samples has demonstrated that the phases were well decrystallized. Comparison with the data on the reference standards has indicated high symmetry of the phases (structures) present in the samples. An increase in structural symmetry confirmed the isomorphic incorporation of the elements, i. e., HLW simulators, into the lattices of perovskite, zirconolite and hollandite. The set of synthesized matrices intended for HLW immobilization appears to be quite extensive. In this paper, as an example, data are provided only on two types of such matrices: titanate ceramics of the Synroc type and stabilized cubic zirconia.

It should be noted that cubic zirconia has higher porosity compared to titanate ceramics. Probably the best results can be obtained by increasing the solid phase synthesis pressure or time. Surface fragments of titanate ceramic and zirconium dioxide samples were photographed by an electron microscope. The titanate matrix, in comparison with zirconium dioxide, is denser and practically devoid of porosity (Table 1).

At the same time, the difference in the porosity of the samples did not have a significant effect on the leaching rate of HLW elements (simulators) from the obtained matrix samples, which in case of Synroc amounted to 10^{-7}—10^{-8} g/(cm²·day). At the same time, in case of cubic zirconium dioxide samples this indicator accounted for $0.5 \cdot 10^{-9}$ g/(cm²·day).

Along with porosity and the leaching rate, there are other characteristics that are taken into account when the quality of certain materials is evaluated. The latter account for the stability and the durability of the synthesized materials to mechanical stress, the possibility of shifts in the bedrock layers at the disposal sites and the thermal load from the radioactive decay of nuclides present in the matrices.

Experiments have demonstrated that for titanate ceramics, the elastic modulus was almost similar to the one of Synroc, whereas for cubic zirconia, this indicator has turned out to be lower.

The microhardness of the matrix samples was measured according to a standard method (Vickers method). The tests showed that for cubic zirconium dioxide the microhardness amounts to 4.9 GPa and for titanate ceramics it was found to be equal to 14.4 GPa. For Synroc this indicator amounts to 8.4 GPa.

Uniaxial compressive strength was measured for the studied samples as well. The results were as follows: 389 MPa for cubic zirconia, 1 490 MPa for titanate ceramics and 574 MPa for Synroc.

Thermal expansion coefficients for the samples were calculated as well. The following values were obtained considering a temperature range of 20—500 °C: cubic zirconium dioxide $(7.4—57.9) \cdot 10^{-6}$ K^{-1}, titanate ceramics — $(8.2—8.5) \cdot 10^{-6}$ K^{-1} and Synroc — $10.5 \cdot 10^{-6}$ K^{-1}. Thus, the physicochemical properties of the synthesized titanate ceramics turned out to be in many respects similar to those of the Synroc.

Thermal resistance of fuel materials in nuclear power is often evaluated using a parameter called the thermal strength coefficient, M:

$$M = 2\delta_y \lambda (1-\nu)/\alpha E, \quad (1)$$

where δ_y stands for yield strength; λ is the thermal conductivity.

It presents the maximum heat flux that can possibly pass through a plate of a unit thickness at which the maximum thermal stress in the plate reaches the resistance limit δ_γ. If we substitute it with another strength characteristic corresponding to potential material degradation mechanism, the parameter M modification can serve as a thermal resistance characteristic for the matrices. For the studied matrices, the compression force (δ_c) is considered as the most important quantity: it is this value that should substitute δ_y in the equation (1). Therefore, to compare the matrices considering the criterion of their thermal resistance, the M_c characteristic can be used:

$$M_c = 2\delta_c \lambda (1-\nu)/\alpha E, \quad (2)$$

where δ_c stands for the ultimate compression pressure.

This parameter allows to evaluate the synthesized matrices and to compare them with the Synroc. Table 2 summarizes the M_c calculation results.

Table 2. Calculated thermal stress coefficients for different matrices

Parameters	Cubic zirconium dioxide	Titanate ceramics	Synroc
$\alpha \cdot 10^{-6}$, K^{-1}	7.4	8.2	10.5
δ_c, MPa	389	1490	574
λ, W/m·K	1.26	2.1*	2.1
ν	0.28	0.30	0.30
E, GPa	40	150	134
M_c, 10^3	2.39	3.56	1.19

* Due to the absence of data on Synroc thermal conductivity.

As follows from the data obtained, the titanate matrix is characterized by the maximum thermal strength coefficient.

In addition to the synthesis of mineral-like compositions, under the studies performed by the Radium Institute large focus was placed on the search of methods providing the immobilization of iodine-129. Despite the low specific activity (180 mKu/g), this isotope poses a serious threat to the biosphere due to its long half-life ($T_{1/2} = 1.57 \cdot 10^7$ years) and high mobility in various media.

Studied were various cements, bitumens and etc. Iodine leaching rate from the compounds based on Portland cement containing lead and barium iodides amounted to 10^{-4} g/(cm²·day). For various bituminous compounds, when the degree of iodine salt filling was not higher than 50 wt.%, the leaching rate ranged from 10^{-6} to 10^{-4} g/(cm²·day).

For the case of controlled iodine disposal in the form of poorly soluble compounds constituting to various compositions, the task of iodine-containing waste treatment was reduced to the inclusion of these compounds into compact compositions resistant to external influences. The Radium Institute implemented relevant studies. Copper iodide precipitate, as well as copper iodide with the addition of metallic copper powder were chosen as such a form. The obtained samples were studied to identify the rate of iodine leaching and the mechanical and thermophysical stability of the matrices.

Weakly acidic solution (pH = 1—3) of potassium iodide with the radioactive isotope iodine-125 introduced into it ($T_{1/2} = 60$ days) were precipitated to determine the leaching rate by a radiometric method. A copper nitrate solution was used as a precipitant with an addition of a hydrazine nitrate to reduce elemental iodine to iodide. Elemental iodine was formed from the copper iodide precipitate.

Another technique was used to simulate the process of copper iodide precipitation from alkaline solutions formed when radioiodine is captured from gas streams. Hydrazine nitrate was introduced into an alkaline solution containing iodine in the form of iodide and iodate to reduce iodate to iodide:

$$3I_2 + 6NaOH = 5NaI + NaIO_3 + 3H_2O,$$

$$2NaIO_3 + 3N_2H_4 = 2NaI + N_2 + 6H_2O.$$

Then, a radioactive isotope of iodine was introduced assuming the same chemical form, neutralization was performed and the acidity of the solution was adjusted to pH = 1—3. Finally, the $Cu(NO_3)_2$ precipitant was added. The generated Cu_2I_2 precipitate was separated from the solution on a glass filter, washed with a nitric acid solution (0.1 mol/L) and dried for 4—5 hours at a temperature of 110—120 °C. The bulk density of the resulted copper iodide sediment amounted to 2.82 g/cm³.

To obtain compact samples, a copper iodide precipitate (or a mixture of a dry copper iodide precipitate with a metallic copper powder) was pressed on a mechanical ten-ton press or in a gas-stat.

Densities of the Cu_2I_2 samples produced on a mechanical press and in a gasostat were quite similar: 5.47 and 5.51 g/cm³, respectively, which is 97.3 and 98.0% of the single crystal density being equal to 5.62 g/cm³.

Tests focused on the iodine leaching from the samples were implemented under static conditions according to the MSS-1 method [10]. Iodine fraction released into the solution was measured using a radiometer by measuring the counting rate of the solution sample. Table 3 summarizes the test results. On the first day, the rate of iodine leaching from copper iodide samples amounted to $2.6 \cdot 10^{-4}$ g/(cm²·day), which appeared to be comparable to the equilibrium indicator for cement compositions. Subsequently, after 112 days it decreased and became almost constant — $0.67 \cdot 10^{-5}$ g/(cm²·day). This value appeared to be comparable to the rate of iodine leaching from bituminous compositions with a filling degree of no more than 50%. Relatively high rate of leaching in the initial period could be apparently explained by surface defects of the samples produced by the pressing.

Presence of an additional barrier (metallic copper) results in a decreased leaching rate. For samples with this additive (Table 3), the initial iodine leaching rate was found to be 1—2 orders of magnitude lower compared to the one of copper iodide samples, i.e., the interaction of the resulting free iodine with metallic copper resulted in the initial compound and, therefore, to a decrease in the iodine leaching rate.

Table 3. The rate R, g/(cm²·day) of iodine leaching from the samples of copper iodide and copper iodide with metallic copper

Composition	Time, days	$R \cdot 10^{-5}$, g/(cm²·day)
Cu_2I_2	1	26
	4	3.7
	59	1.1
	212	0.67
$Cu_2I_2 + Cu_{met}$ (20 wt.%)	1	0.64
	7	$6.08 \cdot 10^{-2}$
	14	$4.13 \cdot 10^{-2}$
	28	$1.54 \cdot 10^{-2}$
	42	$8.19 \cdot 10^{-3}$
$Cu_2I_2 + Cu_{met}$ (50 wt.%)	1	1.19
	7	$4.95 \cdot 10^{-2}$
	14	$7.61 \cdot 10^{-3}$
	28	$3.55 \cdot 10^{-3}$
	42	$3.17 \cdot 10^{-3}$

Axial cold pressing at a pressure of 150 and 250 MPa was used to produce samples with metallic copper. The copper content in these samples was ranging from 10 to 70 wt.%. Their leaching rate was studied as well (Table 4). As for the pressing time, it was initially found that an increase from 1 to 30 minutes had little effect on the properties of the samples. In this regard, the pressing time in all experiments was the same and amounted to 2 min.

Table 4. Pressing conditions, sample characteristics and iodine leaching rate

Copper content (metal), wt.%	Pressing conditions and sample properties			Leaching rate R, g/cm²·day		
	Pressing pressure, MPa	Density, g/cm³	Sample weight, g	Leaching time, days		
				1	7	28
50	150	5.09	2.389	$1.06 \cdot 10^{-6}$	$1.15 \cdot 10^{-7}$	$3.20 \cdot 10^{-8}$
50	150	5.05	2.394	$2.37 \cdot 10^{-6}$	$4.36 \cdot 10^{-7}$	$1.80 \cdot 10^{-7}$
50	250	5.40	2.812	$1.29 \cdot 10^{-6}$	$3.80 \cdot 10^{-7}$	$4.01 \cdot 10^{-8}$
50	250	5.46	2.373	$0.57 \cdot 10^{-6}$	$3.02 \cdot 10^{-7}$	$5.15 \cdot 10^{-8}$
50	250	5.34	2.369	$1.17 \cdot 10^{-6}$	$4.01 \cdot 10^{-7}$	$2.39 \cdot 10^{-8}$
70	150	4.85	2.436	$1.86 \cdot 10^{-6}$	$3.63 \cdot 10^{-7}$	$2.20 \cdot 10^{-8}$
70	250	5.50	2.4401	$1.66 \cdot 10^{-6}$	$5.27 \cdot 10^{-7}$	$2.34 \cdot 10^{-8}$

The samples were heated under this process (below the decomposition temperature of copper iodide), which could significantly increase their density and reduce the porosity. Thus, at a temperature of 260 °C, the density of the obtained sample amounted to 7.88 g/cm³, which appeared to be significantly higher compared to the maximum density (6.64 g/cm³) of the same sample from cold pressing. Certain critical pressure (P_{cr}) level was found above which the density of the samples did not increase and their open porosity did not change.

Studies using scanning electron microscopy have shown that at a macrolevel, the surface could be characterized as smooth, with no noticeable roughness and secondary cracks. Basic material had a finely dispersed structure of rounded particles with a size of 0.5—3 microns. The composition of the samples was studied by X-ray phase analysis. For cold-pressed samples, the results of the study showed that the composition was identical with the initial one. However, up to 10% of cuprous oxide was found in the samples produced by hot pressing which was due not only to metallic copper oxidation, but also to copper iodide decomposition.

In addition to the leaching rate, mechanical and thermophysical properties of samples with metallic copper (Young's modulus — *E*, shear modulus — *G*, compression modulus — *K* and Poisson's constant — ν) were studied as well. Table 5 presents the results obtained. Table 5 shows that the mechanical properties of the matrices depend little on the material composition and the pressing force. Matix strength increases along with an increase in the pressing pressure and the content of metallic copper in the sample. The most durable matrices were found to contain 70 wt.% of copper.

Table 5. Pressing conditions and characteristics of samples with their compositions based on a mixture of copper iodide and metallic copper

Copper content (metal), wt.%	Pressing conditions and characteristics of the samples					
	Pressing pressure, MPa	Density, g/cm³	*E*, GPa	*G*, GPa	*K*, GPa	ν
10	150	5.09	23.81	9.23	18.89	0.29
20	150	5.05	23.01	8.77	20.41	0.31
10	250	5.40	28.68	10,68	27.00	0.32
20	250	5.46	28.66	10.82	27.30	0.32
30	150	5.34	24.88	9.63	19.94	0.23
50	150	4.85	13.78	5.76	7.56	0.20
70	150	5.50	23.21	8.82	20.91	0.32

At the same time, taking into account the fact that given such a copper content, the iodine load is significantly reduced, matrices containing 30—50% of metallic copper can be considered as those having optimal composition.

Thus, it can be concluded that the developed technology and the resulting samples of crystal

matrices are suitable for iodine-129 immobilization purposes [11].

Conclusion

The use of hot isostatic pressing (HIP) is considered as a most promising method providing the synthesis of matrices for subsequent radionuclide isolation. The idea of gasostat application in the nuclear sector was first proposed back in 1956 in the USA (Battelle Memorial Institute) to produce fuel elements for a nuclear reactor [7].

In addition to HLW reprocessing, another promising HIP application is the selection of compositions for spent nuclear fuel immobilization, which, for one reason or another, cannot be disposed of at operating plants or their reprocessing is considered economically infeasible. A large amount of such fuel has been accumulated in our country and abroad, including the SNF from research reactors, transport installations and many other sources. Temporary SNF storage in containers cannot provide safety for hundreds and thousands of years. This problem will become even more pressing during the decommissioning of nuclear power plants, when it's necessary to unload all the spent fuel from the reactor pools, including damaged fuel assemblies.

When talking on the prospects and the experience of HIP method application, one should not forget about the difficulties and problems on the way of its implementation in the radiochemical industry. As it comes to gasostats, the challenge faced is the high-pressure level that can be reached only in a small chamber (with a small sample size), hence such installations are characterized with low efficiency. Its operation requires sophisticated systems to provide high pressure, heating, control and monitoring. The technology and the equipment applied at all preliminary stages to generate powders for solid-phase synthesis are no less sophisticated. Also, one should not forget that safety should be provided and the impact of harmful factors on the service personnel should be minimized.

Given the modern level of technological development, equipment operation and its control can be automated via local control systems (LCS), whereas loading and unloading material operations can be robotized. Maintenance operations are to be implemented remotely. In the future, the robotization of the process will increase the performance with no need of engaging some additional personnel for maintenance operations. Given the accepted concept of immediate equipment dismantlement at shutdown NPPs [12], development of the HIP technology implying the robotization of technological operations is considered as an extremely urgent task to be addressed.

The accumulated knowledge and its application are seen as a prerequisite for high performance when planning new research. It also holds out the prospect of simpler pressing units requiring no complex systems and minimum preparatory operations that can be developed in the future. In this case, joint work of technologists and designers would result in some engineering solutions that are supposed to be much-in-demand at industrial facilities for the final HLW disposal or during the management of damaged SNF at decommissioned nuclear facilities.

Perhaps not all the provisions expressed in the article can be considered indisputable, but the authors hold out a hope that the presented materials will be carefully analyzed and taken into consideration during the development of relevant plans on the application of the HIP method.

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Information about the authors

Pokhitonov Yurii Alekseevich, Ph.D., Leading Researcher Fellow, JSC V. G. Khlopin Radium Institute (28, 2nd Murinsky ave., St. Petersburg, 194021, Russia), e-mail: ypokh@khlopin ru.

Starchenko Vadim Alexandrovich, JSC V. G. Khlopin Radium Institute (28, 2nd Murinsky ave., St. Petersburg, 194021, Russia).

Dalyaev Igor Yuryevich, Deputy Chief Designer, Federal State Autonomous Scientific Institution "Central Research and Development Institute of Robotics and Technical Cybernetics" (21, Tikhoretsky ave., St. Petersburg, 194064, Russia), e-mail: igor@rtc.ru.

Titov Sergey Lvovich, General Director Deputy, LLC Design Institute Petrohim–Technology (4, letter A, Kantemirovskaya st., St. Petersburg, 197342, Russia), e-mail: titovsl@yandex.ru.

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