1. INTRODUCTION.

It can be literally said that further development of nuclear-power engineering will be finally determined by a possibility of safe treatment of radioactive wastes with prevention of their contact with the biosphere. Isolation and prevention of environment radioactive contamination determined a necessity of concentration and solidification of radionuclide, which could be disposed over a long period of time. One of the main and necessary conditions for creating stable and safe radioactive wastes is maximal moisture removal with a maximal degree of their concentration in the binder [1].

The experience of operating existing systems of preliminary radioactive water purification at Nuclear Power Plant showed that one of the important and unsolved problems is improving the efficiency of removal of dispersed admixture from radioactive water. Low rate of suspension removal of the existing technology leads to sludge getting into radioactive wastes that makes the operation of the vaporiser difficult, to setting of deep concentration by evaporation, and, what is also very important, it leads to increase in quantity of liquid radioactive wastes.

2. RESEARCH ON PROPERTIES OF RADIOACTIVE WATERS SUSPENSION.

The technology of radioactive waters purification from insoluble admixture provides:

- sedimentation of suspension in the sump tank, sedimentation tank and radioactive waters tank,
- filtration of radioactive water through mechanical filter. [2]

The diversity of technological processes with various influences of physicochemical and radioactive factors on Nuclear Power Plant objects leads to formation of radioactive waters containing complicated dispersed systems with little-studied properties.

It is necessary to have information about physicochemical properties of dispersed systems as well as calculation of instability (25…100 m³/hour) of radioactive water
discharge rate for recycling in the sedimentation tank while analysing the efficiency of removal of insoluble admixture from radioactive waters.

The analyses of literature shows the lack of such data and the necessity of conducting experimental research on properties of real radioactive waters suspension while recycling. [1]

Depending on the nature of the dispersed phase and dispersed environment, dimensions of dispersed particles, their bulk concentration and a number of other properties dispersed systems are divided into classes that can have completely different properties. [3]

The main of them, which influence the efficiency of purification, are typical for all similar systems. [3] Among them:

- total concentration of suspended particles;
- phase-dispersed composition of suspension;
- unitized stability of suspensions;
- viscosity of the liquid phase;
- solidity difference between dispersing and dispersed environment;
- suspension particles distribution function according to hydraulic size or distribution density of suspension particles.

During the experimental work on defining properties of suspensions the analyses of phase-dispersed composition of sludge in sump tank, sedimentation tank and radioactive waters tank as well as analyses of concentration of suspended particles and dispersed composition in the purified water were hold according to the technological chain of purification. [4] There was a method was chosen to define dispersed composition of the solid phase and construct differential and integral curves of density of particles distribution according to the size. It is based on separation of suspension by filtering through a line of membrane filters, on which dispersed solid phase was kept with further drying and weighing on the analytical weights [5]. Suspension filtering was hold sequentially through membrane filters ПОР500, ПОР250, ПОР100, ПОР40, ПОР10, ПОР1,0 with gradual reduction of filter cells size. (table 1) Total concentration of suspended particles was defined as a sum of all suspensions kept by the filters. The relative average weigh of suspensions fractions in radioactive water was calculated as a sum of relative dispersions of the sludge of sump tank, sedimentation sedimentation tank and radioactive waters tank.
Table 1

<table>
<thead>
<tr>
<th>Fraction size, microns</th>
<th>Relative average weigh of suspensions fractions in the radioactive water</th>
<th>Relative weigh of sludge fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sump tank</td>
<td>sedimentation tank</td>
</tr>
<tr>
<td>&gt;500</td>
<td>11,6</td>
<td>28,5</td>
</tr>
<tr>
<td>250…500</td>
<td>15,5</td>
<td>22,6</td>
</tr>
<tr>
<td>100…250</td>
<td>22,7</td>
<td>22,8</td>
</tr>
<tr>
<td>40…100</td>
<td>22,0</td>
<td>14,6</td>
</tr>
<tr>
<td>10…40</td>
<td>18,9</td>
<td>8,2</td>
</tr>
<tr>
<td>1…10</td>
<td>9,3</td>
<td>3,3</td>
</tr>
</tbody>
</table>

The poured density of sludge, which was calculated by weighing a sludge sample after drying in the muffle furnace at 105°C, weighing on analytical weights, by defining the volume using a measuring cylinder, constituted for: sump tank 1,26 t/m³, sedimentation tank 1,27 t/m³, radioactive waters tank 1,28 t/m³. The density of suspensions was calculated taking into account real occupied volume which was in the measuring cylinder after adding weighed amount of sludge and constituted for: sump tank 2,42 t/m³, sedimentation tank 2,13 t/m³, radioactive waters tank 1,84 t/m³. The macrostructure of fallouts, size and form of particles were defined by the method of optical microscopy using the microscope of “Эргаваль” type. It was determined that the bulk of sludge was composed of small-dispersed particles, partially coagulated into units. The form of the particles is irregular. The majority of the particles have elongated form with the isomeric rate about two. The minimal dimensions of these sludge particles are: sump tank 15 microns, sedimentation tank 8 microns, radioactive waters tank 1,6 microns. The median dimensions of the particles are: sump tank 132 microns, sedimentation tank 78 microns, radioactive waters tank 27 microns. In the sludge of the sump tank and sedimentation tank some big particles with the size of more than 1 mm can be observed. The maximum size of the particles of the radioactive waters tank is 340…380 microns. Therefore, the solid phase of sludge of the sump tank and sedimentation tank is several times more large-dispersed compared to the solid phase of sludge of the radioactive waters tank. However there are rather big particles in the radioactive waters tank, and in the sump tank and sedimentation tank only suspensions with the size over 380 microns can be efficiently purified.

The measuring of the hydraulic size was performed by Stocks’ formula. The Stocks’ formula is applicable to Newtonian liquid at small Reynolds numbers (Re<2) as well as to diluted suspensions with high unit stability of the system and stability of the internal properties of the particles [7]. The hydraulic size must be reduced with the
reduction of the equivalent diameter of a particle, which has been proved by the calculations based on the test data (table 2).

Table 2

The hydraulic size of Nuclear Power Plant radioactive waters sludge suspensions

<table>
<thead>
<tr>
<th>Median particle size, microns</th>
<th>The hydraulic size of suspensions, mm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sump tank</td>
</tr>
<tr>
<td>500</td>
<td>286,0</td>
</tr>
<tr>
<td>375</td>
<td>161,0</td>
</tr>
<tr>
<td>175</td>
<td>35,0</td>
</tr>
<tr>
<td>70</td>
<td>5,6</td>
</tr>
<tr>
<td>25</td>
<td>0,71</td>
</tr>
<tr>
<td>5</td>
<td>0,029</td>
</tr>
</tbody>
</table>

However $U$ is also a function from viscosity and density. Therefore, it is also from temperature, salt-containment, concentration, composition of suspended particles and other factors. Thus the test data calculated by Stocks’ formula provides a range of values, which define domain of dependence of hydraulic size of the radioactive water suspensions on equivalent diameters of suspensions (drawing 1). The present domain is built on the basis of test data of suspensions properties and operational characteristics of the sedimentation tank in Khmel’nitsk Nuclear Power Plant.

There was a connection between diameter of suspension entrainment and discharge of the recycled radioactive water (drawing 2) set to define dependence of the purification quality on the discharge rate of water supplied to the sedimentation tank. Taking into account Stock’s formula these dependences characterize also the necessary hydraulic size of suspensions. The range of diameter of entrainment can be put down as an inequation.

\[
d_{y \min} \leq d_y \leq d_{y \max},
\]

\(d_{y \min}\) is an equivalent diameter of entrainment under the most favourable conditions of sedimentation tank operation, microns;

\(d_{y \max}\) is an equivalent diameter of entrainment under the most unfavourable conditions of sedimentation tank operation, microns.

While defining dependences a combined coordinate system was used: natural logarithm \(d_y\), microns and radioactive water flow \(F\), m\(^3\)/min (drawing 2). The interval of change of radioactive water rate in the sedimentation tank was 0,4 … 1,7 m\(^3\)/min. Semi-logarithmic coordinate system allowed to describe the calculation data by...
Technical section

equation of lines out of which the empirical dependences of $d_{y\text{ max}}$ and $d_{y\text{ min}}$ on $F$ for the tested sedimentation tank were found.

$$d_{y\text{ max}} = 35.80 \exp(1.76F), \quad (2)$$

$$d_{y\text{ min}} = 10.65 \exp(1.76F). \quad (3)$$

Taking into consideration that $F = SV$, where $S$ is a square of the sedimentation tank, m$^2$, $V$ is a speed of rise, than relation between (4) and (5) can be shown as follows

$$d_{y\text{ max}} = 35.80 \exp(0.83 \frac{F}{S}), \quad (4)$$

$$d_{y\text{ min}} = 10.65 \exp(0.83 \frac{F}{S}). \quad (5)$$

\textbf{Drawing 1.} Range of values of hydraulic size $U$, mm/sec, depending on suspensions diameter $d_{\mu}$, microns: 1- favourable conditions of operation, 2 - unfavourable conditions of operation.
Dependence of diameter of entrainment $d_y$, microns on radioactive water rate $F$, m$^3$/min: 1 – the most favourable conditions of operation, 2 – the most unfavourable conditions of operation.

Those are true for a sedimentation tank with any settling square.

Dependences (4), (5) allow to rewrite the inequation (1) as follows

$$35,80 \exp\left(0,83 \frac{F}{S}\right) \geq d_y \geq 10,65 \exp\left(0,83 \frac{F}{S}\right). \quad (6)$$

Analyzing the data received (see tables 1, 2 and drawings 1,2) and inequation (6) it can be stated that regardless high calculation sedimentation speed of suspensions sludge the majority of them is not drawn out of radioactive waters and comes to the radioactive waters tank.

A reason of such suspensions behaviour in the NPP radioactive waters lies in deviation of their stream from the Newtonian that correspond to [8, 9]. This determines difficult for understanding and description rheological properties. Their explanation and prediction demand creation and application of complex approaches and numerous methods.

3. RESEARCH ON SLUDGE COMPRESSION PROCESSES

Research results [4] give an idea about dispersed composition and macrostructure of NPP radioactive waters sludge, process of their sedimentation and allow to define the hydraulic size of diluted suspensions with high unit stability of the system and stability of the internal properties of the particles.
However single settling of the particles is possible only in the mono-dispersed unit-stable system, when the particles during sedimentation do not change their form and size. At the same time, while settling NPP radioactive waters, the process runs in poly-dispersed system with a wide range of particles sizes, which become bigger, change their form, density and dimensions during the process of sedimentation. As a result of this the speed of their sedimentation changes.

Because of the unit instability (and sedimentation instability of NPP radioactive waters sludge consequently) the kinetics of their clarification and compression was defined by means of technological simulation of settling real sludge of the sedimentation tank of Khmel’nts’k NPP in the laboratory cylinders of different height. The cylinders were made of Plexiglas and were graduated along the full height in order to measure the volume of the compressed sludge [12]. To prepare a sludge solution, samples of sludge were prepared and thoroughly mixed in water with the volume equal to the volume of the cylinder (table 4). The weigh of the sample was chosen depending on the sludge concentration in the high-concentrated sludge streams coming into the sedimentation tank.

Table 4

<table>
<thead>
<tr>
<th>Model number</th>
<th>Cylinder height, mm</th>
<th>Weigh of sludge sample, g</th>
<th>Cylinder volume V₀, decimeters³</th>
<th>Sludge concentration in the prepared solution C₀, g/decimeters³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>400</td>
<td>20,0</td>
<td>2,00</td>
<td>10,0</td>
</tr>
<tr>
<td>Model 2</td>
<td>800</td>
<td>40,0</td>
<td>4,00</td>
<td>10,0</td>
</tr>
<tr>
<td>Model 3</td>
<td>1200</td>
<td>60,0</td>
<td>6,00</td>
<td>10,0</td>
</tr>
</tbody>
</table>

After mixing the tested sludge solution was put into cylinders, in which periodically, after specific time intervals of settling they marked the movement of border line between purified water and compressed sludge. The typical peculiarity of small-dispersed sludge is their compression, not sedimentation, i.e. the movement of border line between liquid and sediment downwards with sediment density increase. Movement of the border line between liquid and sediment was measured every two minutes. Test was stop if there border line between liquid and sediment was not moving during 10 minutes.

At quite long time of compression the process slows down, the value of solid phase concentration (Cₜ) moves to some constant.

At \( \tau = 0 \), \( C_\tau = C_0 \), and at \( \tau \to \infty \), \( C_\tau \to C_\infty \).

(7)

Where \( C_0 \) is sludge concentration at initial moment, g/decimeters³.
Technical section

$C_t$ is sludge concentration at present moment, g/decimeters$^3$;

$C_\infty$ is sludge concentration at infinite compression, g/decimeters$^3$;

$\tau$ compression time, minutes.

The average sludge concentration was calculated basing on the initial sludge concentration in the volume occupied by the sludge at present moment of time. As sludge weigh is constant and during the process of compression only the volume occupied by it changes, then the following comes from the equation of the balance:

$$C_t = \frac{C_0 \cdot V_0}{V_\tau}, \quad (8)$$

Where $V_0$ is the volume of sludge solution at initial moment, decimeters$^3$;

$V_\tau$ is the volume of sludge solution at present moment, decimeters$^3$;

In order to make interpretation of the test data completely accurate and to raise reliability of the conclusions made, the most probable value of the tested value and calculations by (8) of the sludge solidification process the curves (drawing 3) were constructed based on the results of the curves averaging using the method of the smallest squares.

**Drawing. 3.** Change of sludge concentration $C$ (g/decimeter$^3$) and sludge volume $V$ (decimeter$^3$) while compression from time $t$ (min): 1c, 1v – model 1; 2c, 2v – model 2; 3c, 3v – model 3.

The test data of the NPP radioactive waters sludge compression process was processed with method of approximation using the exponential function:
\[ C_t = C_0 + (C_\infty - C_0) \left( 1 - \exp \left( -\frac{t}{k} \right) \right) \] \hspace{1cm} (9)

Where \( k \) — a constant of sedimentation speed, minutes\(^{-1}\).

Expression (9) in the view:
\[ C_t = B - A \exp \left( -\frac{t}{k} \right), \] \hspace{1cm} (10)

Where B and A are coefficients connected with the values \( C_0 \) and \( C_\infty \) of the expression (9) in the following way:
\[ A = C_\infty - C_0, \] \hspace{1cm} (11)
\[ B = C_\infty. \] \hspace{1cm} (12)

Values A, B (table 5) were calculated on the basis of initial sludge concentration in the model solution and stabilization of the volume of the compressed sludge (stopping the border line between liquid and sediment). The value of the constant of the concentration speed \( k \) (see table 5) was calculated using in (10) substitution of the values of the found A, B, and the value \( C_\tau \) that lies on the curve (drawing 3) at \( \tau = 30 \) min.

<table>
<thead>
<tr>
<th>Model number</th>
<th>A</th>
<th>B</th>
<th>k</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>111</td>
<td>121</td>
<td>12,68</td>
<td>0,323</td>
</tr>
<tr>
<td>Model 2</td>
<td>110</td>
<td>120</td>
<td>15,86</td>
<td>0,349</td>
</tr>
<tr>
<td>Model 3</td>
<td>109</td>
<td>119</td>
<td>18,27</td>
<td>0,333</td>
</tr>
</tbody>
</table>

As the depth of settling \( H_0 \) in the operating sedimentation tanks constitutes 4 . . . 6 m then in order to recalculate the kinetics of clarification of radioactive waters drawn in the laboratory models for the depth of the real sedimentation tanks, they used a condition of sedimentation similarity, under which equation of clarification effects in the model and real sedimentation tank is observed.

\[ \frac{T_o}{t_m} = \left( \frac{H_o}{h_m} \right)^n, \] \hspace{1cm} (13)

Where \( T_o \) is clarification duration in real, sec;
\( H_o \) is clarification depth in real, m;
\( t_m \) is clarification duration in the model, sec;

\[ Dysnai - 2006 \]
is clarification depth in the model, \( m \); 
\( n \)  — index in the sedimentation similarity, which reflects capability of suspension to agglomeration during the process of clarification.

Indexes of the sedimentation similarity were calculated after comparing the processes of sludge compression for the models with different depth out of the following equation:

\[
    n = \log \left( \frac{h_1}{h_2} \frac{\tau_2}{\tau_1} \right),
\]

(14)

Where \( h_1, h_2 \) are cylinder heights of the models 1 and 2 correspondingly.

\( \tau_1, \tau_2 \) are time of sludge compression before concentrating \( C_r=110 \text{ g/decimeter}^3 \) of the models 1 and 2.

High convergence of the sedimentation similarity index calculation results shows its independence from relation of the real and model depth of sludge compression (see table 4)

Formula of approximation (10) and calculation (13) allows to define dependence of change compressed sludge concentration on time:

\[
    C_r = C_\infty - (C_\infty - C_0) \exp \left[ -\frac{\tau}{k} \left( \frac{H_k}{h_m} \right)^n \right],
\]

(15)

Where coefficients \( k \) and \( n \) are defined during simulation of the compression process on the models.

After data processing of KhNPP high-concentrated radioactive sludge of the sedimentation tank compression simulation this dependence may have the following view:

\[
    C_r = 121 - 111 \exp \left( -\frac{\tau}{6.52} \right).
\]

(16)

The speed of suspended solid particles and liquids may be increased by the action of centrifugal forces. The essence of water clarification in hydrocyclones and centrifuges is based on moving a particle to the periphery by the centrifugal force during water rotation.

The method of filtering through a mechanical filter was replaced with a two-stage centrifuging, and this was chosen as an optimal way of improving the technology of radioactive waters suspension purification.
4. CONCLUSIONS

So, the results shown give an idea about process of sedimentation and solidification of high-concentrated NPP radioactive waters sludge as well as after running a laboratory simulation, give a possibility to estimate compression processes with real heights of sedimentation tank.

The results give an idea about dispersed composition and macrostructure of NPP radioactive waters sludge, process of their sedimentation and allow to define dependency of efficient entrainment diameter on suspensions properties and of sedimentation tank characteristics.

Using centrifuging plant solves the following problems:

- radioactive waters clarification from heterogeneous admixture;
- accumulated sludge recycling;
- free bulk in Liquid Waste Storage.

Moreover, the suggested technology reduces radioactive wastes to 1 m$^3$/year of the solidified wastes and 195 m$^3$/year of the spillages bottoms, allows to significantly save on heat, water, reagents, tar as well as provides long-time and safe storage of radioactive wastes under simplified conditions.

REFERENCES