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Experimental justification of strainer meshes of NPP sump

Экспериментальное обоснование сеток фильтров баков-приямков АЭС

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Ключевые слова: гидравлические исследования; дебрис; потери напора; расход; теплоизоляция; фильтрующее устройство

Abstract. Processes of filter meshes clogging of emergency core cooling system sump intended for cleaning water incoming in recirculation system from sump are studied. Test rig for study of hydraulic characteristics of filter elements, which is a closed circulation loop are described. Basic principles of modeling of coolant recirculation through a filter element, occurring in event of an emergency depressurization of primary circuit, and experimental research methods are presented. Dependences of pressure drop on meshes on flow rate and amount of debris for several types of meshes on ordinary and borated water are obtained and analyzed. It is shown that the use of borated water leads to an increase in both time to reach steady state and pressure loss on meshes. Constructive measures to reduce pressure losses are proposed.

Аннотация. Изучены процессы засорения сеток фильтров бака-приямка системы аварийного охлаждения зоны, предназначенных для очистки от загрязнений воды, поступающей в систему рециркуляции из баков-приямков. Описана экспериментальная установка для исследования гидравлических характеристик фильтрующих элементов, представляющая собой замкнутый циркуляционный контур. Приведены основные принципы моделирования рециркуляции теплоносителя через фильтрующий элемент, происходящей в случае аварийной разгерметизации первого контура, и методика экспериментальных исследований. Получены и проанализированы зависимости перепада давления на сетках от расхода и количества дебриса для нескольких видов сеток на обычной и на борированной воде. Показано, что использование борированной воды приводит к увеличению как времени достижения установившегося режима, так и потерь давления на сетках. Предложены конструктивные мероприятия для уменьшения потерь давления.

1. Introduction

At analyzing possible accidents at nuclear power plants (NPP), special attention should be paid to sudden depressurization of reactor cooling circuit caused, for example, by rupture of primary circuit pipeline. Naturally, intensity of course of such an accident, its various hydrodynamic, thermal and force effects depend significantly on size of suddenly created hole through which coolant will flow out. In all countries, including in Russia, for a maximum design accident a sudden transverse rupture of main circulation circuit pipeline with simultaneous flow of coolant from both ends is adopted.

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In case of accidents involving rupture of pipelines with high parameters there are destruction of thermal insulation, structural elements and structures. Part of garbage (debris) formed during accident can get into water intake devices for recirculation systems and disable these systems.

Since system contains a coolant with a high temperature (~300 °C) and at a high pressure (~160 kg/cm^2), a sudden decrease of pressure results in boiling of water and formation of steam. Within a short interval of time, main part of coolant in volume of ~300 m^3 flows through gap. During this period pressure and temperature under containment of reactor compartment increase, heat transfer in reactor core sharply worsens, temperature of fuel elements rises and it depressurization may occur. On pressure decrease signal in primary circuit, high and low pressure of emergency core cooling system (ECCS) pumps are automatically turned on, and borated water is supplied from sump of containment. On pressure increase signal in containment sprinkler pumps are automatically turned on and water is injected into air space of containment to condense steam and remove heat from atmosphere of containment.

Function of sprinkler system is also cooling of water to provide acceptable temperature conditions during operation of emergency core cooling system pumps (high and low pressure emergency injection systems). At the stage of long-term recirculation, the water taken through sumps serves for removal of residual heat during post-accidental cooling of reactor core.

Reliability of emergency core cooling system and removal of heat from containment depends on failure-free operation of pumps, which in turn depends on degree of clogging of meshes – filter active of ECCS sump designed for cleaning from contaminations of water entering in recirculation system from sumps. Clogging of grids and filters with elements by damaged pipeline rupture thermal insulation and other debris reduces supply of pumps and can cause it increased vibration and intensive cavitation wear. Meshes used for filtering the sumps diverse in designs and parameters. Results of tests allows determine most effective mesh for clogging of debris at minimum head loss on it.

For control of impurities coolant recirculation system must be equipped with filter structures, functioning and proper operation of which by means of tests must be checked. These tests should be carried out in chemically specific conditions using insulation of appropriate excerpt and coating material.

Based on analysis of operational experience of various stations, regulatory documents have been developed that establish requirements for water intake devices for recirculation systems and a methodology for ensuring these requirements, compulsory component of which is determination of hydraulic characteristics of filter elements depending on it contamination and specific flow rate of coolant [1–6].

Therefore, researches of aspects complex of sump operation in various operating conditions and development of constructive measures based on obtained results to ensure it trouble-free operation are carried out [7-26]. Thus, the works [7–12, 14, 16] are devoted to studies of composition, properties, characteristics of debris, and its modeling. Chemical properties of coolant and debris are discussed in the works [13, 17, 20, 23]. The results of physical and mathematical modeling of the motion of a coolant with debris particles, including through filters, are given in [15, 18, 19, 21–26].

In Russia, such researches have been carried out since beginning of 21st century [27–30], while experiments become more complicated and ever closer to real conditions of hypothetical accidents. Particular attention to this was paid after the accident at the Fukushima NPP, the study of causes and effects of which to a large number of studies are devoted [31–33].

This paper describes experimental hydraulic researches of meshes and slotted gratings of filter elements, results of which can be used as input data for justified determination of required filter surface and for design of filter active of ECCS sump. The results are deliberately conservative due to horizontal arrangement of meshes, as a result of which all debris introduced into flow reached it, without possibility of sedimentation from entering in unit to test mesh of strainer.

2. Methods

Hydraulic characteristics of filter elements depending on type of debris, amount of debris and reduced flow rate of coolant (nominal flow through model – nominal flow through 1 channel, reduced to area of tested mesh) were determined. During tests:

- type and brand of insulation, included in composition of debris, corresponded to those, that will be used in reactor building of NPP;
- quality of insulation (density, humidity, fractional composition, etc.) corresponded to characteristics of insulation exposed to steam (steam-water) jet during destruction;

- as filter elements were researched a slotted filter and meshes with a cell size of 1.0 mm and 0.7 mm;
- research section (pipe) with installed filter element in its hydraulic characteristics corresponded to full-scale.

Scope of tests included:

- determination of hydraulic characteristics (dependence of pressure losses on specific flow rate) of a "clean" filter element;
- determination of hydraulic characteristics (dependence of pressure losses on specific flow rate and quantity of insulation) of element contaminated with insulation;
- determination of effect on hydraulic characteristics of additional contaminations (sand, paint coatings), chemical agents (boric acid H_3BO), etc.

Solve technical tasks, by experimenting with models, possibly, if use notion of similarity of physical phenomena: research of clogging process of a filter element fragment (grid or mesh) of ECCS sump filters is possible when there is a correspondence between characteristics of nature and its model and, knowing characteristics of nature and form of this correspondence (similarity), one can find characteristics of nature.

Created model corresponded to basic similarity conditions, since were researched filter element fragments with fragments of destroyed natural insulation and other debris of same brands, sizes and other characteristics as in nature (debris included various fractions of artificially aged insulation fragments, sand, clay, zinc, particles and paint plates). At the same time, research at same flow rate of coolant and debris in terms of 1 cm^2 of mesh, as in NPP conditions was carried out. The time modeling scale is one. Thus, geometric (scale 1:1) and kinematic similarity were provided.

The only difference from nature is use of water at temperature of 20 °C instead of 95 °C. However, this approach is conservative because of increase in water viscosity.

One of main objectives of research is research of filter device clogging in order to develop recommendations aimed at ensuring trouble-free operation of "sump–pump" system. Hydraulically, containment device is a local resistance in a system including supply pipeline, pump, discharge pipe. For stable normal operation of this system it is necessary that pressure in inlet pipe of pump is not less than cavitation margin allowed for given pump brand.

Results of numerous tests have shown that hydraulic performance of pump inlet connections is a function of Froude number Fr. Other dimensionless parameters (for example, Reynolds numbers Re and Weber We) have a secondary meaning. In our case (with respect to filter mesh) Froude numbers on model and in nature are equal:

$$\mathrm{Fr}_{\mathrm{mod}} = \mathrm{Fr}_{\mathrm{nat}} = \frac{v_{\mathrm{p}}}{\sqrt{gh}},$$

where v_p – fluid velocity in pipeline; h – static head in pipe above mesh, g – acceleration of gravity. For example, at $v_{\mathrm{p}} = 0.012$ m/s and $h = 1$ m number of Froude is $\mathrm{Fr} = 0.0038$.

Value of local resistance coefficient of filter mesh ζ_{m} reflects the loss of pressure Δh_{m} when liquid flows through it:

$$\zeta_m = \frac{2g\Delta h_m}{v_p^2}.$$

Thus, by measuring flow rate and pressure drop on contaminated mesh on model, it is possible to calculate its resistance coefficient corresponding to volume of debris that has been introduced into water per unit area of mesh.

Clear size of mesh cell d_{cell}, like velocity of flow through it V_{cell}, is the same for model and nature. Therefore, Reynolds number

$$Re = \frac{V_{cell} d_{cell}}{\nu}, \tag{1}$$

where ν – kinematic viscosity coefficient, at 20°C $\nu_{20} = 1.01 \cdot 10^{-6}$ m^2/s.

In Table 1 shown the values of Reynolds numbers calculated at this temperature at a nominal flow rate of water of 0.0947 m^3/h, and also at a flow rate of 0.5 m^3/h.

Table 1. Velocity V_{cell} and Reynolds numbers Re

Mesh	**Clear size of mesh cell**		**Flow rate of water**			
			0.0947 m^3/h		0.5000 m^3/h	
	m^2	%	V_{cell}, m/s	Re	V_{cell}, m/s	Re
Cell 0.7 mm	0.013	47	0.0020	1	0.0107	5
Cell 1.0 mm	0.015	51	0.0018	2	0.0093	6
Slot 1.0 mm	0.010	35	0.0026	3	0.0139	9

Thus, for all tested filter devices in entire range of flow rates, the Reynolds numbers ranged from 1 to 9, indicating a laminar flow near meshes. This conclusion was confirmed experimentally (visually when particles of debris move), when turbulent flow at beginning of working section below diffuser was observed. Next, almost to confuser, flow mode remained laminar – particles moved linearly vertically downward.

Therefore, dependence of pressure drop (in other words, the head loss) on filter device of flow rate must be linear. In addition, it does not depend on pressure ahead in front of filter device with debris that has settled on it, which can be considered as a porous material. However, for obtaining each of these dependencies for a different amount of debris requires a certain amount of time, and when performing tests under influence of water flow there was compaction of debris settled on mesh, and pores of settled debris are clogged with small particles, which introduce a certain nonlinearity. These processes were especially noticeable in borated water (tests on cold water were carried out, then some of it on borated water were repeated).

The researches in test rig consisting of a closed circulation circuit (Figure 1) in which filter meshes were located horizontally on working section of rig, which introduced additional conservatism in obtained results were carried out: entire debris, with exception of smallest particles passing through mesh, settled on it, unlike actual filter modules, when particles with larger hydraulic size settle to the bottom before it enter directly to filters. Horizontal filter configuration did not assume a reflection of its real location, but served only to ensure development of a homogeneous layer with well-defined characteristics.

In Figure 2 on a larger scale fragment of working section with installed in it filter element (red color is given to sealing rings) is shown. A photo of filter element prepared with a stainless steel mesh is shown in Figure 3.

Pressure drop across filter element, as well as pressure before and after it, by differential pressure sensors MP5010 DP and piezometers mounted on rings for selection and averaging of pressure were fixed (Figure 4). Results of flow rate and pressure measurements entered to computer by data acquisition and processing software were processed.

Since total design area of filter surface of one channel is preliminary, it was necessary to carry out tests in such way that it results could be used both with decreasing and with increasing this area. Such change leads to corresponding change as well as in amount of debris per unit area and flow rate of coolant through mesh (and flow rate associated with it on model).

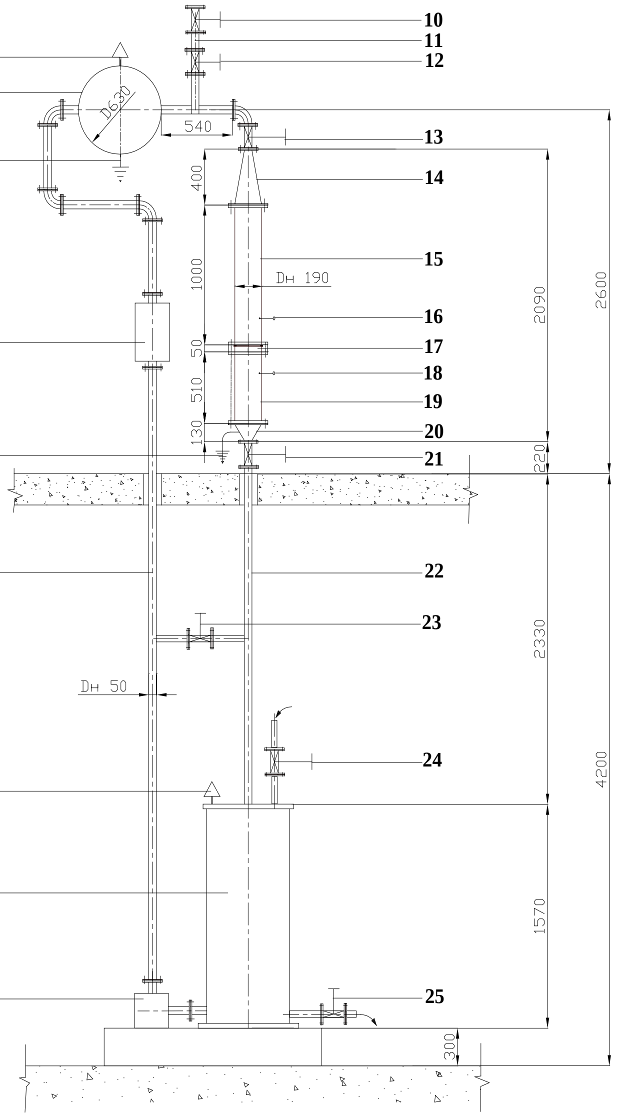

Figure 1. Scheme of test rig: 1 – pump, 2 – lower tank, 3, 9 – air bleed valve, 4 – pipeline inlet section, 5, 7 – drain outlet, 6 – flow meter, 8 – upper tank, 10 – gate valve upper, 11 – gate for debris introduction, 12 – gate valve lower, 13 – valve upper, 14 – diffuser, 15 – supply pipe of working section, 16, 18 – pressure sensor, 17 – detachable section with a filter element, 19 – outlet pipeline of working section, 20 – confuser, 21 – valve lower, 22 – outlet section of pipeline, 23 – bypass valve, 24 – water inlet valve, 25 – water drainage valve

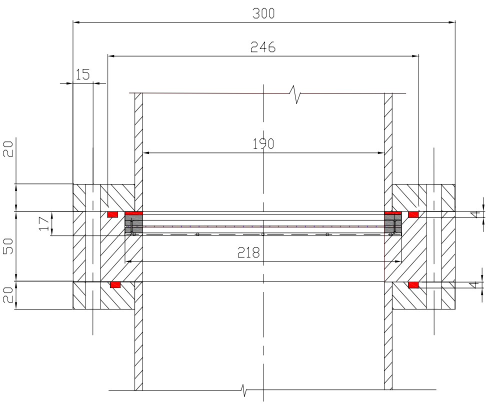

Figure 2. Fragment of working section with filter element

Figure 3. Filter element

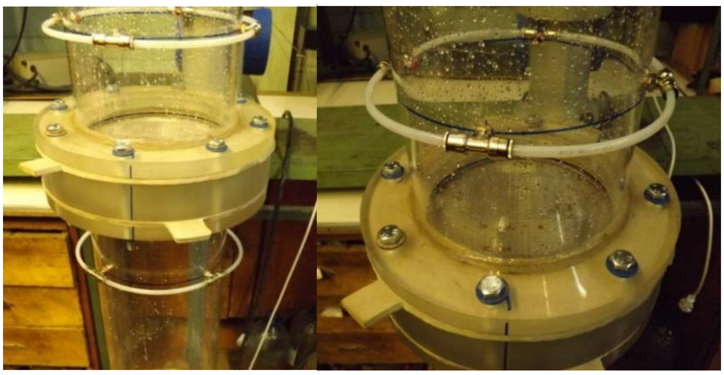

Figure 4. Rings for selection of pressure

Therefore, tests to cover entire range of possible changes in these parameters were designed. Tests with a different amount of debris, ranging from 0 to 150 % of nominal with a step of 25 % (in first tests) and 15 % were carried out. Here, for nominal amount of debris its weight per area of testing mesh on model for given area of filter surface of one channel is taken. At the same time, flow velocity at approach to filter (and hence flow rate through mesh) in first tests was up to 20 nominal (which corresponding to flow rate of model approximately 2 m^3/h), in further (after processing first obtained results) – to 5 nominal (flow rate approximately 0.5 m^3/h). This range of velocities covered and possible unevenness of velocities in lower and upper parts of future filter module, related both to nature of meshes clogging by debris, and to parameters of modules and collector.

Debris after appropriate preparation was packaged, receiving either 10 portions of debris at 15 % of nominal amount per 1 channel, or 6 portions of 25 % (Figure 5).

Figure 5. 25% of dry debris

Soaking of debris an hour before first introduction into flow of test rig was carried out, which corresponded to time interval between possible accident and beginning of debris arrival to meshes of strainers.

Tests simulated behavior of filters in first few hours after possible accident with loss of coolant. In general case, if further analysis of results of tests does not indicate otherwise, they were carried out in following sequence.

1. Soaking debris portions in approximately 800 ml of water.
2. Test rig was turned on, head loss on mesh on clean water was measured, flow rate of about 0.5 m^3/h was set.
3. One hour after soaking of debris, first portion (15 %) through gate was introduced.
4. After 10 minutes first measurement of flow rate and pressure drop was made. Within 10 minutes almost entire visually visible part of debris on mesh was settled (Figure 6), mode became steady, and measured characteristics ceased to change significantly. For borated water process, as before, remained unsteady.
5. Then flow rate by four steps to minimum level was reduced, after that it to original 0.5 m^3/h was returned. Measurement of flow rate and pressure drop in each mode 5 minutes after flow rate change was carried out. Thus, duration of one cycle was 35 minutes.
6. Next portion of debris was introduced, after which actions of two preceding paragraphs 4 and 5 were repeated. If, at a flow rate of 0.5 m^3/h, pressure loss exceeded test rig limit of 1.8 m, initial flow rate before introduction of debris was reduced and set so, that in 35 minutes, taking into account possible

growth of difference on mesh, pressure loss did not exceed 1.8 m. However, in some tests with large amounts of debris flow rate was not regulated forcefully, it decreased spontaneously during growth of resistance coefficient of clogged filter. However, time intervals between measurements were maintained as before.

7. Mesh with settled debris at the end of test was removed, dried and determined weight of debris delayed by mesh.

8. Mesh with fine cell of 0.1 mm was installed and at flow rate up to 15 m^3/h water in test rig debris particles not delayed by mesh being tested was cleaned, as long as pressure drop and flow rate did not cease to change with time.

9. At the end of cleaning fine mesh with settled particles of debris was removed, dried and determined weight of debris not delayed by test mesh of filter.

after introduction of debris portion:

after 10 seconds **after 10 minutes**

Figure 6. View of work section after introduction of debris portion

3. Results and Discussions

In course of research dependences of head loss on different filter meshes for various amounts of debris was obtained. At flow rate up to 0.5 m^3/h in absence of debris pressure drop for all tested meshes was zero. As an example, test results for 1.0 mm mesh are given.

Research of 1.0 mm mesh on water

In Figure 7 shown general view of debris delayed by mesh. Separate plates of paint are clearly visible.

Figure 7. Dried debris on mesh

In tests with debris a very wide dispersion of pressure drop values is observed, which is associated with a significant dependence of these values on character of the fall and packing of debris on mesh, which occurs at random. With larger meshes this spread should decrease. However, with a conservative approach to design and calculations, it is recommended to be guided by largest (worst) values of pressure drop.

In Figure 8 shown dependence of difference on mesh on amount of introduced debris at nominal flow rate of 0.0947 m³/h. Results of tests in form of graphs of dependences of difference on mesh with debris on flow at different amounts of introduced debris are given in Figure 9.

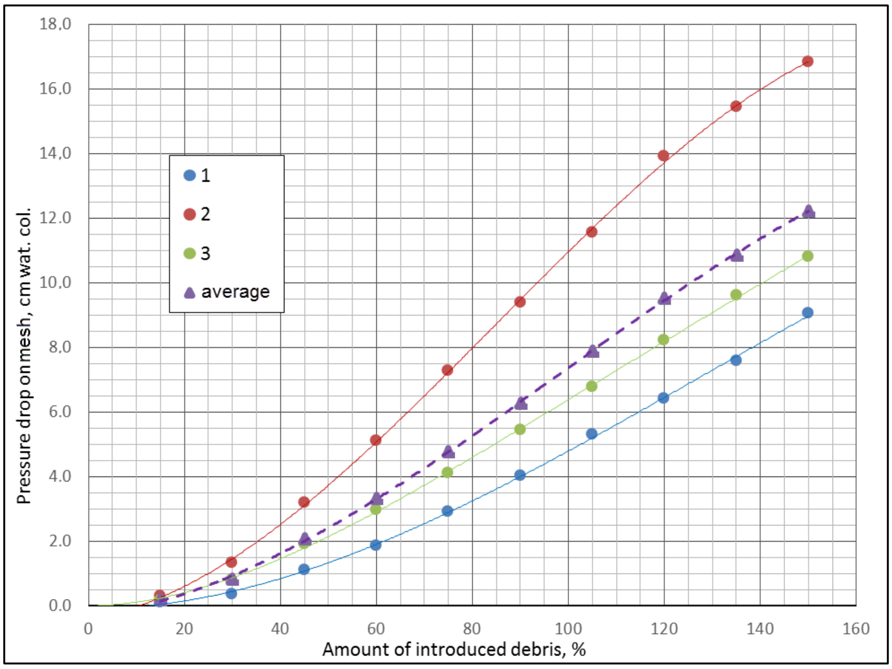

Figure 8. Dependence of pressure drop on filter with mesh of 1.0 mm on amount of debris at nominal flow rate of 0.0947 m^3/h for tests 1, 2 and 3

Maximum drop at nominal flow rate of 0.0947 m³/h and 100 % of debris was about 11 cm, which is more than 3 times lower than for mesh with a cell of 0.7 mm. Pressure loss on mesh in these tests has a smaller spread and smaller average values than in tests with cell of 0.7 mm: average difference on mesh is 1.0 mm with 105 % of introduced debris and flow rate of 0.5 m³/h was about 57 cm (in tests 28, 36 and 61 cm), whereas on mesh with cell of 0.7 mm it is 99 cm (in tests 33, 79 and 184 cm).

In Table 2 shown weights of introduced and delayed debris by filter mesh with a cell of 1.0 mm for three tests. Weight of debris not delayed by filter was up to 22 %, in three tests from 78 to 95 % of debris was delayed. At the same time, relation with head loss was reversed: with maximum weight of delayed debris pressure drop was minimal, with minimum weight – maximum. This shows that greatest influence on drop when debris falls accidentally exerts nature of its distribution along mesh.

Table 2. Weights of introduced and delayed debris on filter mesh with a cell of 1.0 mm

Test number	**Weight of debris**		
	introduced, g	**delayed**	
		g	%
1	139.0	131.7	95
2	139.0	109.1	78
3	139.0	116.3	84

Long-term test on borated water of mesh with a cell of 1.0 mm

A long-term test is most indicative from point of view of measuring maximum difference on mesh, since it shows its magnitude in fully stable mode when all debris particles have already settled on filter, including those that passed through mesh initially. During a continuous test lasting more than 52 hours water performed approximately 10 turns.

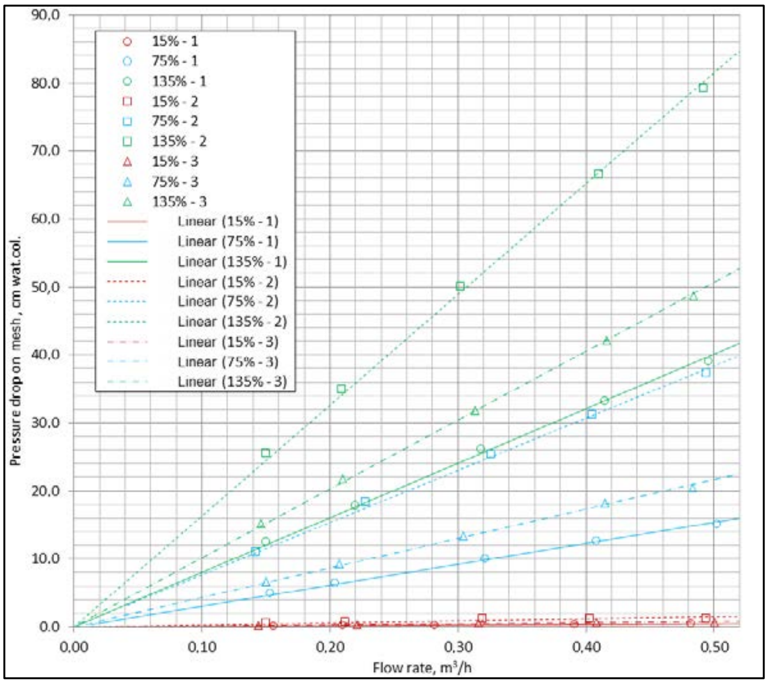

Figure 9. Dependence of drop on filter with mesh of 1.0 mm on flow rate for tests 1, 2 and 3 at various amount of introduced debris

Test without paint plates was carried out: it is heavy and drown in both conventional and borated water. Therefore, a low fence around strainers or small rise it above floor will prevent these plates getting to meshes, which will significantly reduce pressure loss on strainers.

Test at constant flow rate of 0.150 ± 0.005 m^3/h (with decrease of flow rate, by opening valve below working section was increased) was carried out. This is approximately in 1.5 times more than nominal, which is conservative solution, as it causes more pressure losses on mesh, including due to stronger compaction of debris.

In addition, debris by portions of 5 % at intervals of 20 minutes was introduced, which also leads to more uniform tightening of mesh by debris and stronger compaction. At the same time, first 60 % of debris within three hours forty minutes after beginning of test was introduced (in Figure 10 shown a photograph of filter with settled debris after 23 hours 45 minutes after beginning of test), another 40 % - within two hours twenty minutes after day after beginning of test (in Figure 11 shown a photograph of filter with settled debris after 52 hours 35 minutes after beginning of test).

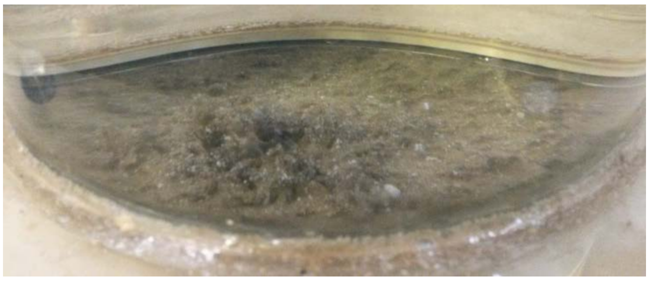

Figure 10. Mesh with a cell of 1.0 mm with 60% of debris without paint plates, borated water

Figure 11. Mesh with a cell of 1.0 mm with 100% of debris without paint plates, borated water

In Figure 12 shown pressure and flow rate graphs during test. It can be seen that growth of pressure losses on mesh continued even after introduction of both 60 % and 100 % of debris, but at slightly slower rate. It ceased only 45 hours after beginning of test (18 hours after introduction of 100 % debris) and remained unchanged for more than 7 hours until end of test, amounting to only 24 cm.

Mesh with delayed debris from test rig after hysteresis test was removed. Thickness of delayed debris in wet state was about 3 mm. On mesh with cell of 1.0 mm 49.6 g of debris was delayed, which is 73 % of introduced 68.0 g of debris. This approximately corresponds to proportion of delayed debris in ordinary tests. However, in reality, weight of delayed debris was larger, since part of it was lost (passed through mesh) when water from test rig to remove filter module was drained.

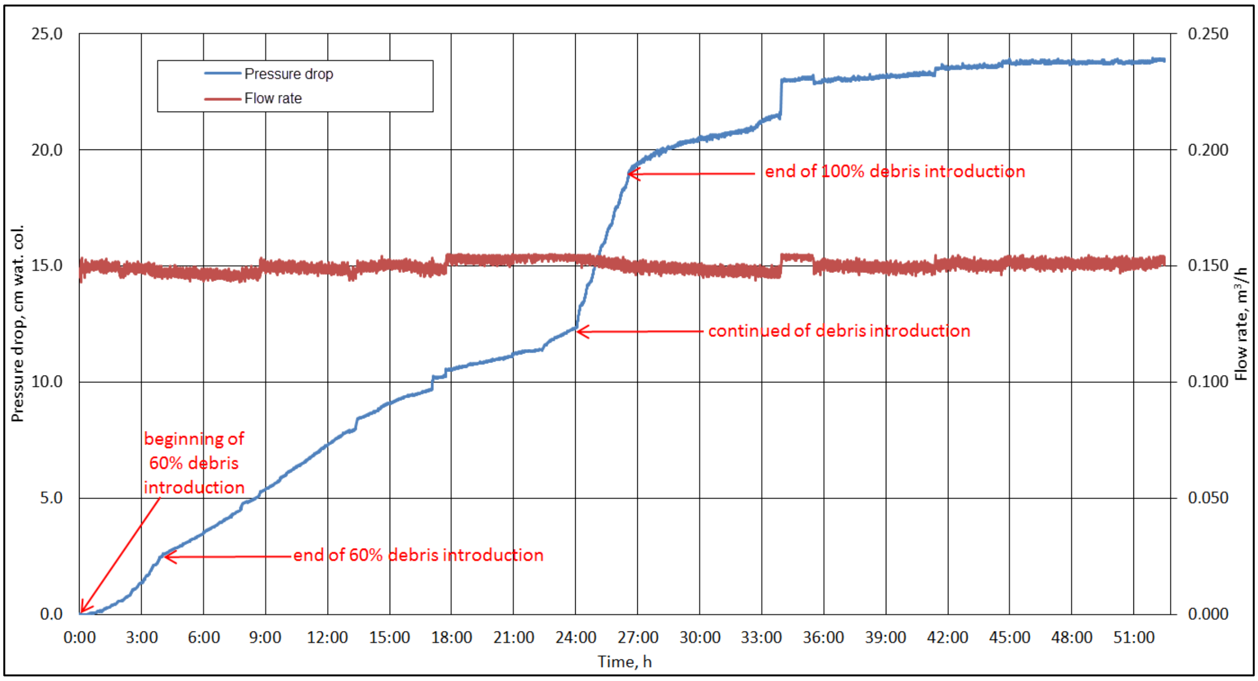

Figure 12. The change of difference on mesh with cell of 1.0 mm over time, borated water

Hysteresis test on borated water

Immediately after end of long-term test, without turning off pump, test to determine dependence of drop on debris of flow rate with determination of flow rate at which pressure loss on mesh is 150 cm of wat. col. was started, as well as to determine hysteresis, which allows determine how completely compacted debris on mesh in conditions that are as close as possible to actual ones. The results of continuous recording of this test are presented in Figures 13 and 14.

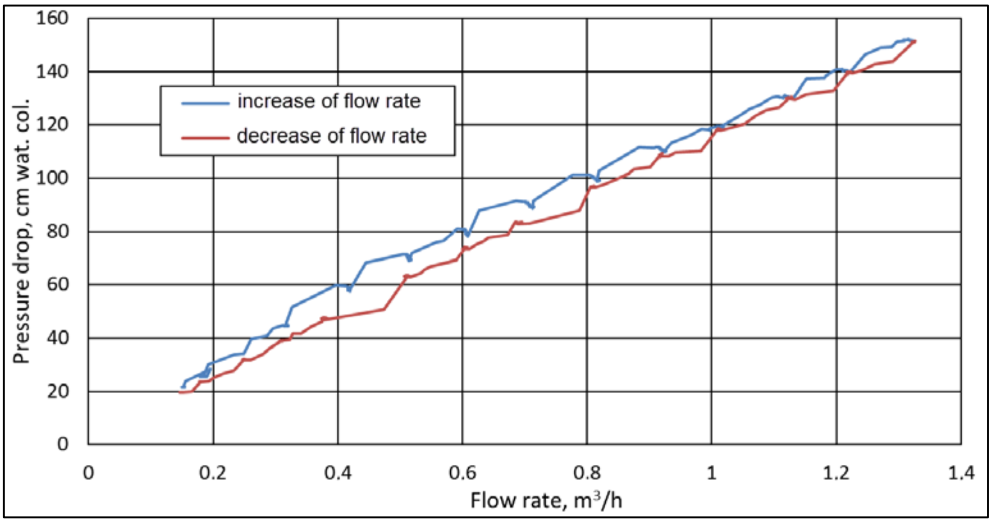

Figure 13. Dependence of drop on mesh with cell of 1.0 mm of flow rate after long-term test, borated water

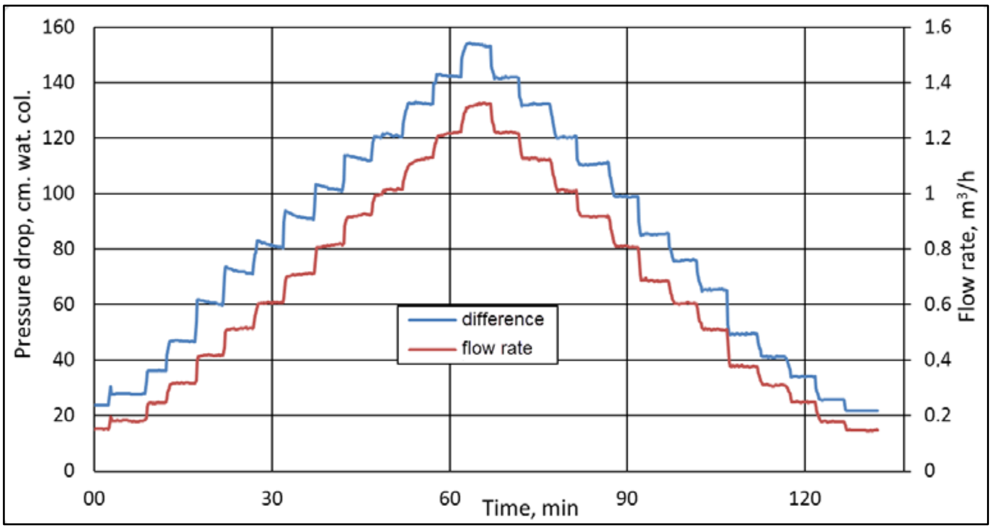

Figure 14. The change drop on mesh with cell of 1.0 mm when flow rate is changed, borated water

The difference reached 150 cm of wat. col. at flow rate of about 1.25 m^3/h, and after reducing flow rate again to level of 0.15 m^3/h, it even became 2 cm of wat. col. below original. Thus, there was no further compaction of debris, and at high flow rates, perhaps, there was an insignificant flushing out of individual particles from debris delayed by mesh. This confirms validity of conclusion that after 45 hours of fluid circulation during long-term test process of pressure losses growth on mesh ceased.

4. Conclusion

1. In tests with debris a very wide dispersion of pressure drop values is observed, which is associated with a significant dependence of these values on nature of fall and packing of debris on mesh, which occurs at random. With larger meshes this spread should decrease. However, with a conservative approach, it is recommended in further calculations to be guided by largest (worst) values of pressure drop.
2. Borated water, apparently, prevents fine particles of debris from sticking together in flow, so they settle longer, but it can be seen colmatage of filtration passages in layer of delayed debris by mesh, and pressure drop on mesh is approximately 10 times greater than in tests with ordinary water, with equal flow rates and amounts of insulation. Wherein, time to reach steady-state mode increases substantially, when flow rate and pressure loss on mesh stabilize. 30 minutes after introduction of debris portion (total amount reached 75%), pressure drop across with cell of 1.0 mm was about 75 cm at nominal flow rate of 0.0947 m^3/h.
3. Research of filter clogging process with separation of debris into two types (paint plates and rest) showed that it joint flow to filter leads to a sharp jump-like increase in pressure drop. Thus, at nominal flow rate of 0.0947 m^3/h with introduction only plates, the difference on mesh with cell of 1.0 mm was zero, with introduction of various debris without plates – from several centimeters in standard tests to thirteen after long-term test. At the same time, when it was jointly introduced in amount of already 90 %, pressure loss was not less than 75 cm.
4. Paint plates are quite heavy and quickly drown in both conventional and borated water. Therefore, a low fence around strainers or small rise it above floor will prevent these plates getting to meshes, which will significantly reduce pressure loss on filters.
5. Due to above factors, the results obtained with a long-term test are most indicative and approximate to real conditions of hypothetical accident, with exception of coolant temperature. At the same time, the difference on mesh with cell of 1.0 mm in steady-state mode (more than 51 hours after beginning of debris introduction) was: at nominal flow rate of 0.0947 m^3/h – about 12 cm, at flow rate of 0.5 m^3/h – about 68 cm.
6. Results of tests are used as initial data for justified choice of type of meshes and determination of necessary filtering surface at designing of filtering devices of ECCS sumps.

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