Development of Passive devices for emergency protection of fast Reactors


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Abstract. The role of passive safety systems (PSS) in increase of reactors safety NNP is reviewed. Development in SSC RF IPPE of a PSS for fast reactors with sodium coolant is analyzed. The expert estimation of a degree of usefulness of different types of PSS for reactors such as BN is conducted.

1. INTRODUCTION

Accidents at the nuclear power plant in Three-Mail-Island in 1979 and it is especial at the Chernobyl nuclear power plant in 1986 have resulted in essential growth of concern all over the world by achieved level of nuclear power safety. The present stage of nuclear power engineering development is inextricably related with perfection of the nuclear power plants with the purpose of increase their safety. Today on the first place not productivity of nuclear power stations is put but their safety. Virtually, the further development of nuclear power engineering depends on whether the effective and strong solutions of safety problems are found in the nearest future or not. There is no doubt that even one severe accident at nuclear power plant could finally undermine the population’s confidence. The nuclear industry should create significant reserves of safety at nuclear power plant.

Proceeding from this and considering the saved up operating experience of working nuclear power plants and new, more rigid safety standards, the problem of development a new generation reactors with the increased level of internal safety is put. Internal safety means ability reactors systems to prevent accidents with core destruction without participation of emergency protection systems or operator actions due to use only internal nuclear, thermohydraulic and mechanical feedback for maintenance of core in safe conditions. The basic direction of the decision of a problem in view is the further development of properties of self-security of the nuclear power plants, and, first of all, nuclear reactors, by a combination of safety properties and Passive Safety System (PSS).

Numerical estimations of development of scripts beyond the design-basis accident have shown, that in fast reactors with sodium coolant, by virtue of their physical features, it is possible to avoid core damages even at the heaviest scripts of accidents with accompanying refusal of active elements of core system if to provide small influence on reactance passive means.

Quantitative illustration of a role of the Passive Safety System serve, for example, the results of japanese researchers Okada K., Tarutani K., Shibata Y. which have shown, that probability of development of heavy accidents such as ULOF, UTOP, ULOHS for fast reactor DFBR, at bringing of the Passive Safety System in structure NPP is reduced practically on two order [1].
PSS has a number of advantages in front of traditional active devices. Investigated devices are passive, so their operation occurs on a basis of naturally proceeding processes and irrespective of work of other devices, first of all, energy sources. Thus, PSS are capable to lower a role of the human factor and to provide a principle protection from fool. With the help of PSS of various functional purpose it is possible to divide such difficult and consequently hard predicted, it is especial in extreme situations, technical system as NPP on separate more simple and predicted subsystems and to carry out their protection in case of heavy accident. The Passive Safety System, in principle, may carry out management of beyond the design-basis accident development.

Now in a number of the countries (Japan, USA, France, Russia etc.) are carry out search researches on development of effective Passive Safety System of the various functional purpose, functioning on various physical effects, as traditional so and on new for nuclear power [2, 3]. Growing interest to the Passive Safety System of various functional purpose speaks about their ability simply, evidently and effectively to solve accident protection of technological equipment NPP and, hence, increases of safety of the atomic power station as a whole.

The wide front of conducting works is caused by that fact, that each type of PSS has the advantages (and lacks) and, now, it is inconvenient to define unequivocally what of them appear the most suitable in concrete conditions NPS.

The carried out analysis of scientific and technical sources and patents sources has shown, that, already now is offered more than two hundred the various devices, able to carry out functions of passive devices of an emergency shutdown of fast reactors. The basic known devices on feedback character can be divided on devices operating on:

- to excess of fuel temperature;
- to decrease of the coolant flow rate;
- to rise of coolant temperature.

Work of the first type of devices is based on phase-convertion, for example, fusion [1], sublimation [4] and moving of nuclear fuel. Apparently, the given type of devices will allow to provide most effectively performance of function of safety, but now they poorly technologically are made and improvement stage rather long and expensive should precede their introduction.

On a high level there is development of the devices operating on decrease of coolant flow (pressure):

- owing to increase of neutrons leakage (Japan, GEM) [1];
- by a principle of hydrodynamical containment of an absorber (Russia) [5].

Lacks of considered type of devices is low sensitivity to change of temperature of reactor and its power.

The most widespread now are the Passive Safety System, operating on excess of coolant temperatures. The Passive Safety System of the given type are placed, as a rule, on an exit of nuclear reactor core and them temperature-sensitive element is surrounded by the coolant. When excess of coolant temperature more than limiting-permissible, the element is operating, absorber of neutrons is released and falls under by its body weight in reactor core, translating his in sub-critical condition. The given type of devices is sensitive to increase of temperature on an output from a core in all accidents with ratio disbalance of power and flow rate, and now is developed most intensively.

To the given type of devices are classed also the Passive Safety Systems in which the absorber is not dumped and his is forcedly inject in core. Working elements of such devices begin to operate, as a rule, as a result of temperature expansion of a rigid body or a liquid. But, according to the executed estimations, known devices [2, 5] is rather massive and have appreciable inertia, and this does not give them an opportunity to carry out fast reactor
shutdown, such as fast reactor with sodium cooling, in case of maximal beyond the design-basis accident.

2. DEVELOPMENT PSS FOR REACTORS TYPE BN

2.1. Main requirements to PSS

In SSC RF IPPE practical works on creation PSAP with reference to BN-800 started in 1988 under supervision of Yu.E. Bagdasarov. Main requirements, which demanded from PSAP of BN-800 were formulated by R.M. Voznesensky in next years:

- in accordingly to purpose efficiency and response of PSS should be sufficient for warning of sodium boiling and heavy damages in reactor core and also for damping reactor power at maintenance of mean sodium temperature in reactor core at a secure level;
- the threshold of operating of PSS should be selected so that they did not operate at transient regimes and design accidents;
- the devices of PSS and the schemes of their work should eliminate a capability of the introducing by them of a positive reactivity at any regimes connected with change of flow rate sodium or sodium temperature in the reactor;
- as a impulse which initiate the PSS acting is more preferential to use rise of coolant temperature as most universal testimony of accident connected with a loss of coolant flow rate and with increase of reactor power;
- the efficiency of each PSS should be such that the input of its absorber was fixed by the control system of a neutron flux in under critical reactor;
- the design of PSS should not change a nominal system of refuelling;
- the design and physical principles of PSS acting should whenever possible to eliminate general failures cause for a nominal system of accident protection;
- the functionality of PSS can be tested by modelling of accident processes in the reactor; at impossibility of secure modelling of accident processes directly in the reactor the PSS capacity for work can be tested to indirect signs or on special test section.

PSS should save functionality at reference for reactors BN difficult conditions of exploitation (temperature ~ 600°C, fluence of fast neutrons with E > 0,1 MeV ~ 2⋅10^{21} (neutron/cm^{2})), i.e. PSS should be not enough sensitive to the operational factors.

In the last years the following types of PSS in different degree were worked in SSC RF IPPE:
- the hydraulically fluidized rod;
- the magnetic on the basis of "Curie point";
- on the basis of a hyperthermal effect of form memory;
- on the basis of series of nontraditional physical effects including lyophobic.

Proceeding from used physical effect in temperature-sensitive element, the Passive Safety Systems to operate on excess of coolant temperature, it is possible to divide into groups, functioning of working elements in which is based on:
- linear temperature expansion of rigid body, including bimetals;
- volumetric expansion of a liquid;
- magnetic properties, including on effect of Kuri point;
- effect of form memory;
- melting of working body in LCPS.
2.2. Passive safety systems with a hydraulically fluidized rod (PSS-G)

One path of creation of a passive safety system of the reactor at accidents connected with stopping of coolant circulation in 1-st contour and nonfunctioning of nominal protection (accident such as on ULOF) – to allot by passive properties of protection the rods of accident protection. The similar device was designed with reference to the reactor BN-600. The weighting compounds are removed from a rod of accident protection and the throttling washer is installed in an operating section.

The absorptive rod is retained above reactor core by coolant flow if the coolant flow rate through the reactor more than 0.6 $Q_{\text{nom}}$. The rod lowers in reactor core under its weight and reactor is shut down if the coolant flow rate becomes lower than 0.6 $Q_{\text{nom}}$.

**FIG. 1. Arrangement scheme of assembly of accident protection in reactor core BN-600:**
1 – guide channel the sleeve, 2 – rod, 3 – absorber.

The preliminary estimations have shown: input of one rod of accident protection on 4 s later of switching-off of a main circulating pump (MCP) during ~ 7 s restrict the increasing of coolant temperature on output from reactor core to a level 700°C (boiling temperature 920°C). The assembly of passive accidental protection (PAP) (fig. 1) consists from guide channel-sleeve (1) and rod located in channel (2). The sleeve is tubular channel: the guide pipe is located inside of channel and hydraulic brake is located in bottom. A rod is cylindrical design consisting of many links, which connect by hinges. The working link, lengthening link and connecting link and also the head for connection with claw of drive bar are links of this design. At the lifted position of a rod the claw is uncoupled from a rod head, the trailing-edge of lengthening link is arranged at the height 0.58 m from lower boundary of reactor core and the lower butt of absorber (3) of operating links is arranged at the height 0.016 m from high boundary of reactor core. At a stop of MCP and malfunctioning of accident protection the fall of a rod into core occurs in sodium under weight of rod at the flow rate of sodium below...
0.6 $Q_{nom}$. For prediction of development of an accident it is necessary to know velocity (time) the input of rod into core.

The made device was tested on a hydraulic test section. Classification of investigated PAP assemblies distinguished by a guide pipe diameter, by wire wrapper on an operating link, by number of hinges, by perforation of a shell of a connecting link and by weight of a rod is listed in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>N of breadboard version (rods)</th>
<th>1 (initial)</th>
<th>2 (prototype)</th>
<th>3 (modify)</th>
<th>4 (prototype)</th>
<th>5 (final)</th>
<th>6 (final)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of a guide pipe</td>
<td>78 mm</td>
<td>78 mm</td>
<td>78 mm</td>
<td>78 mm</td>
<td>76 mm</td>
<td>78 mm</td>
</tr>
<tr>
<td>Wire wrap on an operating link</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Number of hinges</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Length of a rod</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.06-2.1</td>
<td>2.08</td>
<td>2.08</td>
</tr>
<tr>
<td>Weight of a rod</td>
<td>17.75 kg</td>
<td>18.25 kg</td>
<td>18.25 kg</td>
<td>17.8 kg</td>
<td>17.8 kg</td>
<td>18.0 kg</td>
</tr>
<tr>
<td>Number of row and flow area of perforation</td>
<td>Six ( f = 1.88 \cdot 10^{-3} \text{ m}^2 )</td>
<td>Six ( f = 1.88 \cdot 10^{-3} \text{ m}^2 )</td>
<td>Six ( f = 1.88 \cdot 10^{-3} \text{ m}^2 )</td>
<td>Four ( f = 2.31 \cdot 10^{-3} \text{ m}^2 )</td>
<td>Four ( f = 2.31 \cdot 10^{-3} \text{ m}^2 )</td>
<td></td>
</tr>
</tbody>
</table>

One-dimensional equation of motion of a cylindrical body with a hole under operating of applied forces was used for substantiation of using of results on model coolant. At fall of body in a reverse flow when accelerations are insignificant (specially on first stages of motion and at continuously varying values of resistances). The quite satisfactory results can be obtained with usage without inertial approaching of equation:

\[
(M/\rho-V)g - a_1 Q^2/D^2 - a_2 w^2 D^2 - a_3 Q w - a_4 D (d Q/d \tau) = 0 ,
\]

where $M$, $D$ and $w$ – weight, diameter and velocity of a rod, $\rho$, $Q$ – density and flow rate of coolant, $\tau$ – time, $V$ – volume of a liquid, displaced by a rod, $a_1$, $a_2$, $a_3$ – factors which are not dependent on thermal properties of coolant, $g$ – acceleration of gravity.

From the solution of expression (1) concerning velocity is possible to receive an approximated ratio for motion time of a body in a channel with different coolants – i and j

\[
\tau_i/\tau_j = \sqrt{(M/\rho_j-V)/(M/\rho_i-V)}
\]

Pursuant to conclusions from expression (1), measurements of fall time of a rod in assembly in experiments on water test section were conducted on a full-scale model of assembly PAP with imitation of change of flow rate in time. Measurements were conducted on relation corresponding to the run down pumps in 1-st contour. The experimental results were compared to calculations.

The experimentally obtained time of rod motion in assembly with guide pipe $\Omega 78$ mm was $\sim$ 6.2 seconds. The time of rod motion in assembly was increased up to 7.2 seconds at transition on guide pipe $\Omega 76$ mm. The values of velocities are satisfactorily agreed with
values from computation (fig. 2). The recalculation results of some hydraulic parameters of PAP assemblies for water to the sodium are listed in table 2.

**FIG. 2. Changing of fall velocity of a rod in PAP assembly from distance at its actuation in a regime cloning a run-down MCP-1 of the reactor BN-600:**
- ○, ○, +, ◆, ◆ – 1-5 – experiment (guide pipe ∅ 78 mm),
- – 6 – numerical solution of an equation of motion.

**Table 2**

<table>
<thead>
<tr>
<th>N of model version</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q_{\text{nom}} ), l/s</td>
<td>5.45</td>
<td>4.08</td>
<td>5.33</td>
<td>3.7</td>
<td>5.33</td>
<td></td>
</tr>
<tr>
<td>( Q_{\text{fr}} ), l/s</td>
<td>7.22</td>
<td>7.22</td>
<td>8.62</td>
<td>10.5</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>( \tau ), s</td>
<td>6.5</td>
<td>5.0</td>
<td>7.0</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sodium</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q_{\text{nom}} ), l/s</td>
<td>6.1</td>
<td>4.57</td>
<td>5.97</td>
<td>4.14</td>
<td>5.97</td>
<td>2.4</td>
</tr>
<tr>
<td>( Q_{\text{fr}} ), l/s</td>
<td>8.09</td>
<td>8.09</td>
<td>9.65</td>
<td>11.8</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>( Q_{\text{rod}} ), l/s</td>
<td>1.04</td>
<td>1.1</td>
<td>1.01</td>
<td>1.16</td>
<td>1.01</td>
<td>1.03</td>
</tr>
<tr>
<td>( \tau ), s</td>
<td>6.1</td>
<td>4.7</td>
<td>6.6</td>
<td>5.5</td>
<td>&lt;8.0</td>
<td></td>
</tr>
<tr>
<td>( Q'_{\text{rod}} ), l/s</td>
<td>0.14</td>
<td>0.10</td>
<td>0.12</td>
<td>0.08</td>
<td>0.12</td>
<td>&gt;0.053</td>
</tr>
</tbody>
</table>

\( Q_{\text{nom}} \) – nominal flow rate through assembly, \( Q_{\text{fr}} \) – flow rate through assembly at emersion of a rod from lower in the upper position, \( Q_{\text{rod}} \) – flow rate through a rod at nominal flow rate through assembly, \( Q'_{\text{rod}} \) – flow rate through a rod in the lower position at \( Q = 0.25Q_{\text{nom}} \).

Advantages of PSS-G design are:
- the simplicity of a principle and wide experience of development of hydraulic systems of a similar type in engineering;
The most essential lacks of the given type of the device:

- malfunctioning at beyond the design basis accidents with conservation of nominal flow rate of coolant (such as UTOP, ULOHS);
- the practical impossibility of work at the low level of flow rates (for example, lower than 0.67 \(G_{\text{nom}}\) with three loops of heat removal);
- the control of a rod position.

2.3. Working device of a passive type on the basis of magnetic materials (PSS-M)

The magnet system of PSS-M with reference to the reactor BN-800 has a permanent magnet and ambient its magnetic wire. In turn magnetic conductor has screen and armature. The absorber is hanged to armature. The design of PSS-M is shown in a fig. 3.

Principle of PSS-M functioning is based on a decrease of its carrying capacity with temperature rise. In the beginning with temperature rise of PSS-M from 20 up to \(300\text{--}400\degree\text{C}\) is watched a small of decreasing of its carrying capacities (~10%) conditioned by temperature changes of a magnetic induction of PSS-M materials. With further rise of temperature take place a fast fall of carrying capacity PSS-M, which caused by deterioration of ferromagnetic properties of material; near to a Curie point they are lost completely and in this connection take place an actuation PSS-M – scission of a armature and body of PSS-M under operating of weight of absorber.

Magnetic hard alloy with a Curie point equal \(~850\degree\text{C}\) is most reasonable as a material for permanent magnet. The permanent magnets made of this alloy, are efficient during
10000 hours at the temperature 550°C and during 50 hours at temperature 650°C without deterioration of their magnetic properties.

The magnetic soft alloy of iron-nickel-cobalt 67NiCo was used as material of magnetic conductor its temperature of a Curie point equal ~635-640°C and also iron-nickel alloy 65Ni with temperature of a Curie point ~ 620°C.

Temperature relation of carrying capacity of PSS-M model sample are shown in fig. 4, its the magnetic conductor is made from iron-nickel alloy 65Ni and also are shown temperature relation of carrying capacity of PSS-M model sample with magnetic conductor from iron-nickel-cobalt alloy 67NiCo.

![Carrying capacity, kg vs Temperature, °C graph](image)

**FIG. 4. Temperature relations of carrying capacity of PSS-M model sample.**

1 – PSS-M, screen material – alloy 65Ni, armature material – St.3.
2 – PSS-M, screen material – alloy 65Ni, armature material – 65Ni.
4 – PSS-M, screen material – alloy 67NiCo, armature material – St.3.

The development of PSS-M model sample with a magnetic conductor and armature from alloy 65Ni on a sodium test section have are shown that the actuation of PSS-M in beyond the design basis accident will happen at the temperature of 596°C through 6,3 s with from the moment of accident beginning at the temperature of which is coming out of reactor core of sodium 710°C, and from bundle of the fuel pins of assembly PAP (passive accident protection) ~ 747°C; thus the own inertial PSS-M makes 3,4 seconds. Actuation PSS-M with a magnetic conductor of alloy 65Ni and armature from steel of an St.3 will happen through 8,2 s at the temperature of 608°C; at the temperature of sodium, coming out of reactor core, 768°C, and from a bundle of the fuel pins of PAP assembly – 840°C; at it own inertial PSS makes 3,6 s.
Outgoing from temperature relation of PSS-M carrying capacity, the magnetic conductor which one is made from alloy 67NiCo, temperature of a Curie point which one is more, than for alloy 65Ni, it is possible to suppose, that temperature of PSS-M actuation will be increased. So the actuation of PSS-M with armature from alloy 67NiCo in beyond the design basis accident will happen at the temperature of 613°C through 8.8 s from the moment of a beginning of accident at the temperature of sodium, coming out of reactor core, 786°C, and from a bundle of the fuel pins of PAP assembly – 874°C; thus the own inertial of PSS-M makes ~ 3.6 seconds. Actuation of PSS-M with an armature of an St.3 will happen through 9.3 s at the temperature of 618°C; at the temperature of sodium, coming out of reactor core, 800°C, and from a bundle of the fuel pins of PAP assembly – 896°C; at it own inertial of PSS-M will make ~ 3.7 s.

Analyzing the conducted work on development of PSS-M model sample it is possible to make following conclusions:

- on the present moment basically the design of PSS-M, under the characteristics (overall dimensions, temperature of actuation, lag effect (inertial), carrying capacity) conforming is designed;
- in a magnet system PSS-M used for a permanent magnet alloy with temperature of a Curie point ~ 850°C, for a magnetic conductor (screen and armature) specially designed iron-cobalt-nickel alloy 67NiCo with temperature of a Curie point 635°C;
- temperature of actuation of PSS-M device 613°C;
- the general lag effect (inertial) of actuation of PAP assembly made from a beginning of accident ~ 8.8 seconds, from which one 3.6 second the lag effect (inertial) of PSS-M;
- the actuation of PSS-M limits temperature rise of sodium on exit of reactor core and on exit of bundle of the fuel pins of PAP assembly, accordingly to values 786 and 874°C;
- carrying capacity of PSS-M in a nominal regime of the reactor considerably surpasses effective weight of a rod of PAP assembly;
- the residual carrying capacity of PSS-M practically misses and, in this connection, it actuations in other beyond the design basis accidents with temperature rise of sodium on exit of reactor core at its nominal flow rate (accidents such as UTOP, ULOHS).

2.4. Passive safety system with memory effect of the form (MEF)

Now worldwide, first of all in USA, Russia, Japan, France, the hundreds alloys with a memory effect of the form (MEF) are makes and studied, that allows to execute selection of alloys with allowance for of different activity factors of this or that device: purpose, temperature regime, working mediums, cost. The alloys with MEF will rather widely be used in different areas of engineering, that allows to make in essence new designs, to simplify and to improve reliability of existing designs. The concern to the given class of materials is explained by combination of unique physical-mechanical properties:

- show of MEF, including reversible, in a broad range of temperatures (from cryogenic up to 1000°C);
- generating of considerable efforts at transition (600 MPa);
- a high degree of a reshaping (up to 99%) at considerable plastic deformation (up to 10%);
- essential specific functionability (10 MJ/m³);
- high damping and sound-absorbing properties;
- cyclical stability.

In engineering most often will be used alloys on the basis of cuprum and nickelid of titanium. The main lack of the reviewed alloys is low forming temperature (less 130°C). The alloys on the basis nickelid of titanium have the best service (operating) properties, and alloys on the
basis of cuprum – economical advantage. Therefore in engineering, where the high reliability is required at a large cycle of works, for example, for executing mechanisms, the alloys on the basis nickelid of titanium are applied. For temperature rise of MEF on the basis of nickelid of titanium are interest its alloys with a palladium, rhodium, iridium, but thus the cost of alloys is hardly increased.

Table 3
The main alloys having MEF at heightened temperatures

<table>
<thead>
<tr>
<th>N</th>
<th>Composition</th>
<th>Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TiNi</td>
<td>&lt;130</td>
</tr>
<tr>
<td>2</td>
<td>Cu-Al-Mn</td>
<td>150–600</td>
</tr>
<tr>
<td>3</td>
<td>Cu-Al-Mg</td>
<td>200–300</td>
</tr>
<tr>
<td>4</td>
<td>Co-Al-Ge</td>
<td>360–400</td>
</tr>
<tr>
<td>5</td>
<td>Co-Al-Si</td>
<td>500</td>
</tr>
<tr>
<td>6</td>
<td>Fe-Ni</td>
<td>525</td>
</tr>
<tr>
<td>7</td>
<td>Ni-Mn-Ti</td>
<td>-200–700</td>
</tr>
<tr>
<td>8</td>
<td>Ti-Nb</td>
<td>260</td>
</tr>
<tr>
<td>9</td>
<td>Ti-Nb-V</td>
<td>50–500</td>
</tr>
<tr>
<td>10</td>
<td>Ti-Au</td>
<td>290–630</td>
</tr>
<tr>
<td>11</td>
<td>Ti-Ta</td>
<td>230–670</td>
</tr>
<tr>
<td>12</td>
<td>TiNi-TiMe, where Me – Pd, Pt, Rh</td>
<td>100–1000</td>
</tr>
</tbody>
</table>

From reduced in the table 3 alloys having memory of the form at heightened temperatures, the alloys on the basis of a titanium and nickelid of titanium are introduced a greatest interest (concern) for perspective passive safety systems as NNP equipment. Together with Institute of Metallurgy Russian Academy of Science for PSS-T of reactors such as BN were designed and tested the alloys on the basis of a titanium (Ti-Ta 30%) and nickelid of titanium (TiNi-NiRh) having a hyperthermal memory effect of form.

In the substantiation of PSS-T on the basis MEF:

- the techniques for calculation of thermomechanical characteristics of working elements of different geometry (laminated, cylindrical springs, Belville’s springs) are designed;
- the corrosion stability of alloys is investigated on the basis of a titanium in liquid metals (sodium, lead);
- influencing of reactor radiation on MEF (up to \(6 \times 10^{20}\) a neutron/cm\(^2\)) is studied.

For reactors type of BN it is represented by most perspective to the PSS-T with working elements on the basis of Belville’s springs (fig. 5.).

The models of PSS-T with temperature of actuation 570°C, value of generated efforts \(~ 50\) kg, response time \(\leq 1\) s and with MEF are made and tested at temperatures 615 and 650°C.

The main problems of development of PSS-T with MEF are connected to the evidence temperature and radiation stability of working elements under conditions of reactors BN type.
2.5. Lyophobic PSS-T

Lyophobic capillary-porous systems (LCPS) consist of a capillary-porous matrix and lyophobic liquid, i.e. nonwetting of matrix. Compensation (stabilization) of pressure occurs due to change of LCPS’s volume at convertible filling (empting) of porous matrix by liquid. Processes in the fusible accident protection devices using lyophobic effect (LPSS) in comparison with process in traditional fusible elements have a number of the characteristic features connected to their nature [7]: reserved energy; generation of efforts; hyper-dilatometry at melting.

In most cases the melting process is accompanied by increase of substance volume (usually on some per cents). One of the reasons of it are technological processes at crystallization, in the even greater degree reducing value dilatometry at melting. Experimental datas received by T.N. Lipchin [8] testify that the value linear shrunk at crystallization of aluminium makes \( \approx 1.8\% \) (\( P=0.1 \) MPa) and \( \approx 0.17\% \) (at \( P=100 \) MPa). Shrinkable porosity of aluminium, which was crystallized under pressure \( P=0.1 \) MPa makes \( \approx 0.3\% \), at \( P=100 \) MPa – \( \approx 0.05\% \) [8].

The size volumetric shrunk for aluminium crystallization at atmospheric pressure may make \( \approx 5.5\% \), that is comparable to effect dilatometry at melting. To lower size shrunk it is possible only at transition to crystallization under high pressure (~100 MPa), that is technically difficultly sold.

Thus, there is a necessity of creation of the complex systems having high and adjustable value dilatometry at melting, for example, LCPS.
Calculation results of dilatometry at working body melting in LCPS are given on fig. 6. The allocated area defines a range of change dilatometry of pure metals, agrees fig. 1.

![Graph](image)

**FIG. 6. The relation between \( \Delta V/V \) in lyophobic system and the matrix porosity.**

From data given on fig. 6 it is visible, that process of an output of the fused working body from pores at appreciable (>5%) open porosity is prevailing. At high porosity dilatometry the effect in LCPS makes tens interests, that on the order surpasses dilatometry directly a working body.

The given circumstance causes interest to use of effect hyperdilatometry LCPS in a number of technical devices, first of all protective.

In the patent №2138086 of Russian Federation [9] the thermal sensitive starting device is offered. The device is contained the elastic container filled by temperature sensitive substance, with the fixed and mobile end. The mobile end is connected to the trigger mechanism. This device is distinguished from similar by the capillary-porous material introduced into the elastic container is not moistened temperature sensitive substance and is filled with him, while the temperature of fusion of substance is corresponds to temperature of operation of the device. The pores radius of material is satisfy to a condition [10]:

\[
 r < \frac{2 \cdot \sigma \cdot |\cos \theta|}{P},
\]

where \( r \) – pores radius; \( \sigma \) – a superficial tension temperature sensitive substances in a liquid condition; \( \theta \) – a regional corner of contact \((\theta > 90^\circ)\); \( P \) – pressure upon the elastic container (sylphon) from external factors.

In the declared device melting temperature-sensitive substances releases the reserved energy determined by equality:

\[
 E = \int P \cdot dV = \int \sigma \cdot |\cos \theta| \cdot d\Omega,
\]

where \( P_L = \frac{2 \cdot \sigma \cdot |\cos \theta|}{r} \) – capillary pressure of Laplace, \( \Omega \) – an interphase surface of contact "liquid temperature sensitive substance – capillary-porous material".

The device consists of the trigger mechanism with the captures holding an absorber of neutrons (fig. 7). The PSS works (releases an absorber) at the given rise of sodium temperature above nominal. Operation of the PSS should prevent of sodium boiling in reactor at conditions of the heaviest beyond the design-basis accident of reactor BN-600 (BN-800) with a stop of 1 circuit pumps, refusal of active protective systems and extraction of PC’s rod.
by efficiency of 0.24% $\Delta K/K$ with maximal velocity from bottom end. Presence of three working elements allows to use substances with different fusion temperature and raises reliability of operation.

If the ambient temperature will exceed critical value ($650...660^\circ\text{C}$) capture is pushed out from the vessel, releasing an absorber of neutrons, operation of the device occurs under action of several independent force factors:

- there is a melting temperature sensitive substance (for example, aluminium or magnesium) first of all on sylphon contour, goffer which are released and under influence of a high-temperature spring sylphon is extended on the size necessary for disclosing of captures and dump of an absorber in core.
- hyperdilatometry at melting of LCPS.
- temperature sensitive substance increases the volume also due to phase transition, temperature and volumetric expansion that also provides lengthening sylphon and force dump of neutrons absorber thus significant efforts are generated.

Thus, the device itself makes effort for clearing an absorber that provides big reliability of operation. For operation of the device it is not necessary of full fusion through temperaturesensitive substances on section of the elastic container since first of all there is a melting temperature sensitive substances on elastic container contour. Therefore the capillary-porous material can be placed in immediate proximity to walls of the container.

Hence, using rather small volume of the elastic container under a capillary-porous matrix filled nonwetting it’s temperature sensitive substance, significant lengthening of the container
is possible to receive it. Using nonwetting capillary-porous matrixes with the various size pores and capillaries allows to adjust effort of operation. Serviceability of devices it agrees the patent of the Russian Federation №2138086 it is experimentally proved at temperatures of operation 66°C (Wood's alloy), 123,5°C (lead-bismuth), 320,9°C (cadmium), 650°C (magnesium), 660°C (aluminium).

Experimental studying of characteristics of sylphon working elements was carried out on purpose-made liquid metal installation. Time of achievement of the maximal lengthening of sylphon was 5 s, velocity of lengthening was approximately constant. After tests sylphon was visually surveyed. Leakings of aluminium and traces of corrosion it is not revealed. Residual axial deformation of sylphon is marked.

The design "sylphon-container" has much higher axial stability. In an offered design questions of accommodation of a high-temperature spring are solved easier. The scheme of the Passive Safety System with three working elements such as "sylphon-container" is given on fig. 7. The experimental substantiation of size of lengthening is executed on breadboard models working elements such as "sylphon-container" (d_s=16 mm, l_s=44 mm, d_c=28 mm, l_c=50 mm). Results of comparison of the given experiments with results of calculations are given on fig. 8.

Let's note the good consent of the given measurements given on fig. 8 and calculation that proves applicability of the developed techniques for estimated calculations of characteristics of working elements of the Passive Safety System.

Estimated calculations of sodium temperature dependence on exit from of a reactor core and the most intense subassembly at beyond the design-basis accident of reactor BN-800 [11] are submitted on Fig. 9.

![Graph](image-url)
FIG. 9. Change of coolant temperature at beyond the design-basis accident of reactor BN-800:

1 – subassembly (maximal); 2 – a reactor.

At modelling of conditions in assembly Passive Accident Protection of the most intense subassembly operation of Passive Safety System occurs in time from 9 up to 12 s (on various effects) from the moment of the beginning of development beyond the design-basis accident. The coolant temperature on an exit of the most intense subassembly thus will make \( \sim 800-850^\circ C \), i.e. essential underheating (more than 100\(^\circ\)C) up to maximum permissible temperature (930\(^\circ\)C) and up to temperature of sodium boiling (960\(^\circ\)C), and as practically double stock on time of their achievement are provided.

Functionability of devices it agrees the patent of the Russian Federation №2138086 it is experimentally proved at temperatures of operation 66\(^\circ\)C (Wood’s alloy), 123,5\(^\circ\)C (lead-bismuth), 320,9\(^\circ\)C (cadmium), 650\(^\circ\)C (magnesium), 660\(^\circ\)C (aluminium).

3. ESTIMATION OF A DEGREE OF PERFECTION OF VARIOUS TYPES OF THE PASSIVE SAFETY SYSTEM

In order to compare various types of Passive Safety System in nuclear reactor some suggestions were made how their main generalized characteristics should be classified [12].

1. Passivity. One of fundamental characteristics allowing for autonomic coming into action only on the event evoking operation of safety system and also allowing for independent action on another active system (for example Control Safety System (CSS) of power source).

In accordance with the recommendations made in [13], to perform qualitative estimations passing from passive till active system, five categories of passivity are distinguished. The systems are triggered actively fall into lowest category.
In keeping with the classification accepted, the systems under consideration here due to mechanical displacement of absorbent must be related to third category (B) with the following characteristics indicated:

- the absence of any external signal, external power sources and external forces;
- the availability of mobile mechanical parts.

2. **Threshold.** The system must produce signal-impulse or the system parameters must be changed that will initiate triggering of transition algorithm from nominal operation to safety function, i.e. an action will be triggered directed to preventing of accidents and limitation of consequences [13-15]. In order to circumvent false signal the system must, where possible, have clearly defined threshold character of operation.

3. **Generation of efforts.** To provide transition from normal operation to safety function, it is essential that energy, difference of potentials or motive force should be available. When operating in nuclear power facilities at working levels of power, the systems under consideration are in strong fields of nuclear reactor (thermal, corrosive, radioactive), which become all the more enhanced during accidents. To ensure the guaranteed change of state the system must generates the efforts, which significantly exceeds the forces of coalescence resulting from possible exposure of operational fields in nuclear reactor (for example, corrosion, thermowelding).

4. **Lag.** The system must be low inertial, permitting reactor shutdown in the event of accident beyond of design basis without significant damage of reactor core. In fast reactors of BN type it is possible to avoid the damage of reactor core by keeping coolant out of boiling.

5. **Multi-channeling.** To maintain reliability of operation the system must be equipped by some means to continue safety functions. It is found to be appropriated that the system operation is based on not one, but some alternating in tandem physical effects.

6. **Resistance to operational factors.** During campaign the system must be sufficiently resistant to radiation, corrosion, and high temperature and also be insensitive to creeping.

7. **Failure safety.** Any failure (for internal or external reason) in any component of the system must not result in safety level to decrease. The materials, which the system consists of, must be compatible with reactor structure and their ingress into coolant must no cause negative impact on reactor operation.

8. **Simplicity and clearness.** Requirements of simplicity and clearness are concerned with as the physical phenomenon used in the system, and the system structure. Preference is given to simple systems based on traditional physical effects, which are well understandable not only for narrow circle of specialists, but population in whole. It is desirable that the system makes it possible to keep illustrative check.

One of disadvantages of the system is a strong dependence of system characteristics on the place of its arrangement within reactor. The sizes of the system are limited by overall dimensions of sitting unit (for example, subassembly head in BN-600 reactor). The PSS introduced into nuclear power facility, as a rule, permits simplifying the design of NPF, in a whole, and interaction “person-machine”, in particular.

9. **Sustainability.** The systems under development have to be based, if it possible, on technologies inherent to nuclear power engineering. To carry out all stages of research there is a need to have available operable experimental base. Cost and time of elaboration must be as small as possible, and be ≤ 1% of reactor cost and take 3-4 years.

During the system characteristics be estimated as qualitatively and quantitatively the following nomenclature is accepted, as it is shown in Table 5.
Table 5.
Nomenclature accepted for SAS

<table>
<thead>
<tr>
<th>N</th>
<th>Nomenclature</th>
<th>Qualitative characteristic</th>
<th>Quantitative characteristic, ( \varphi_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>++</td>
<td>completely satisfactory</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>satisfactory to a greater extent</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>+ –</td>
<td>partially satisfactory</td>
<td>0.50</td>
</tr>
<tr>
<td>4</td>
<td>– +</td>
<td>improvement is needed</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>significant advancement is required</td>
<td>0</td>
</tr>
</tbody>
</table>

To illustrate quantitatively the system options under consideration the normalized (weighted-mean) characteristic of the system was calculated by the following relationship:

\[
K_j = \frac{1}{N} \sum_{i=1}^{N} \varphi_{i,j}
\]

where \( K_j \) – perfection degree for j-th option; \( \varphi_{i,j} \) – perfection degree of i-th characteristic for j-th option; N – number of generalized characteristics of the system, N = 9.

In the frame of the approach accepted the number of perfect system is equal to 1. Thus, the closer to 1, the more perfect the system is.

Table 6 shows results of estimation of basic characteristics of different types of passive safety system made by authors.

Table 6.
Results of estimations of characteristics and perfection degree for different types of PSS

<table>
<thead>
<tr>
<th>N</th>
<th>Characteristic</th>
<th>Type of system</th>
<th>Linear expansion of solid</th>
<th>Volumetric expansion of liquid</th>
<th>Magnetic with Curie point</th>
<th>Form memory effect</th>
<th>Melting in LCPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Passivity</td>
<td></td>
<td>+ –</td>
<td>– +</td>
<td>– –</td>
<td>+ –</td>
<td>+ –</td>
</tr>
<tr>
<td>2</td>
<td>Threshold</td>
<td></td>
<td>– –</td>
<td>+ +</td>
<td>+ –</td>
<td>+ +</td>
<td>+ +</td>
</tr>
<tr>
<td>3</td>
<td>Generation of efforts</td>
<td></td>
<td>+ +</td>
<td>+ +</td>
<td>– –</td>
<td>+ +</td>
<td>+ +</td>
</tr>
<tr>
<td>4</td>
<td>Lag</td>
<td></td>
<td>– +</td>
<td>– +</td>
<td>+ +</td>
<td>– –</td>
<td>+ –</td>
</tr>
<tr>
<td>5</td>
<td>Multi-channeling</td>
<td></td>
<td>– –</td>
<td>– –</td>
<td>– +</td>
<td>– +</td>
<td>+ –</td>
</tr>
<tr>
<td>6</td>
<td>Resistance to operational factors</td>
<td></td>
<td>+</td>
<td>+</td>
<td>– –</td>
<td>– –</td>
<td>+ –</td>
</tr>
<tr>
<td>7</td>
<td>Failure safety</td>
<td></td>
<td>+ –</td>
<td>+ –</td>
<td>+ +</td>
<td>– +</td>
<td>+ –</td>
</tr>
<tr>
<td>8</td>
<td>Simplicity and clearness</td>
<td></td>
<td>+ –</td>
<td>+</td>
<td>+ +</td>
<td>– +</td>
<td>+ –</td>
</tr>
<tr>
<td>9</td>
<td>Sustainability</td>
<td></td>
<td>+ +</td>
<td>+</td>
<td>– –</td>
<td>+ +</td>
<td>+ –</td>
</tr>
<tr>
<td></td>
<td>Perfection degree, ( K_j )</td>
<td></td>
<td>0.47</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.69</td>
</tr>
</tbody>
</table>

The following conclusions can be reached:
By its perfection degree, the PSSs developed on the basis of thermoelectrical effects and, in first turn, on dependence of electrical resistance on temperature noticeably give up their place to other known types and have a number of principal disadvantages (the absence of as generating efforts and multi-channeling).
One of the main disadvantages of PSSs based on temperature expansion of solid is their high lag, one-channeling, the absence of threshold. Since this type is well known and is under development during long time, it is hard to expect a noticeable progress in improvement of their characteristics.

Rather high value of perfection degree is characteristic of PSSs with temperature-sensitive elements based on alloys with high temperature form memory effect (FME), that results from unique combination of physical, mechanical properties securing low lag, threshold, generation of significant efforts. But, at present stage, development of the FME-based PSSs, especially for fast reactors, is rather conjectural. This is due to (1) such systems are poorly investigated, first of all, temperature and radiative resistance of alloys with FME; (2) experimental base for development of working elements has degraded. The use of such type of the system for less power-loaded nuclear facilities and beyond of reactors is thought to be of considerable promise.

Traditional systems with volumetric expansion of liquid have rather high perfection degree; main lines for their improvement are associated, first of all, with imparting threshold properties and multi-channeling.

At the same level of perfection degree as two last types there are PSSs developed now in different countries (France, Russia, Japan, and India). These PSSs are based on variation of magnetic properties at Curie point. The main disadvantages principally inherent to such type are the absence of generated efforts and one-channeling. Some improvement can be achieved, but at the expense of passivity, when turning from the system with permanent magnets to electromagnetic one, where energy is accumulated by compressed spring [2].

Among all types of PSSs considered here, the more perfect is the system based on hyper-dilatometry of working body in LCPS. Lyophobic Passive Safety System is little sensitive to operational factors (temperature level, corrosion, fluency). The advantages of these systems are threshold of operation, generation of significant efforts, small dimensions. Last circumstance allows the microswitches operating with response to temperature exceeding the given level to be developed.

**CONCLUSIONS**

The present stage of development of nuclear power is inextricably related with perfection of NPP with the purpose of increase of their safety. Safety NPP is put now on the first place but not their productivity.

One of directions of a task in view is the further development of properties of decrease of existing properties of safety with additional input of passive accident protection devices. PSS have a number of advantages in front of traditional (active) devices as their operation occurs on a basis of naturally proceeding processes and irrespective of other devices work including energy sources.

Basic researches on development of the effective PSS functioning on various physical effects (both traditional and new to nuclear power) are intensively conducted now in a number of the countries, first of all in Japan, USA, France, Russia and in a number of other countries. At present are offered some hundreds the various devices which are capable to carry out functions of passive devices of protection of nuclear reactors.

Comparison of various types of the Passive Safety System under 9 generalized characteristics (passivity, threshold, generation of efforts, inertial, multi-channeling, stability to operational factors, safety at refusal, simplicity and presentation, conditions of development) and to generalizing parameter – a degree of perfection (K≤1), has shown, that from considered types PSS with reference to fast reactors the most perfect now are fusible lyophobic devices, basically meeting the requirements on all characteristics.

The most worked with reference to reactors such as BN are the PSS:
on the basis of the hydraulically fluidized rod (PSS-G);
• temperature on the basis of magnetic effect and memory effect of form lyophobic (PSS-T).

The project of reactor BN-800 is stipulated three PSS of hydraulically fluidized absorbing rod type by efficiency everyone ~ 0.5 ∆K/K. Efficiency of PSS-T rod makes ~ 0.3% ∆K/K, that is caused by its smaller length. Thus for maintenance of the accepted efficiency (~ 1.5% ∆K/K) in working section such as BN-800 it is necessary to place the 5 PSS-T. It agrees the executed calculations input in reactor BN-800 of negative reactance provides a reactor damping and reactor cool down up to temperature of an overload (230°C) at input ~ 1% ∆K/K a reactor cool down becomes up to temperature ~ 290°C.

In fast reactors with sodium coolant it is possible to avoid serious damages of reactor core even at the heaviest scripts of development of accidents if to provide influence on reactivity with the help of various type of passive safety devices.

It is developed and protected by the patent of the Russian Federation №2138086 lyophobic the fusible accident protection device (fusible safety system) sylphon the type, working at excess of temperature. The device has a number of advantages before known, for example, the technical decision agrees the patent of USA №5051229 (higher sensitivity, threshold operation) and the device agrees the patent of the Russian Federation №2096009 (higher value and adjustability of a working course, smaller inersial).

Functionability of the offered designs is proved experimentally at various temperatures of operation on breadboard models sylphon devices and devices of type the sylphon-container with various lyophobic liquids: Wood’s alloy (T_{mt} = 80°C), an lead-bismuth alloy (T_{mt} = 123.5°C), cadmium (T_{mt} = 320°C), aluminium (T_{mt} = 660°C).

Developed lyophobic fusible passive accident protection devices on excess of temperature are of interest for nuclear power stations of various type, first of all, as passive devices emergency shutdown a reactor and protection of the technological equipment.

REFERENCES


