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ROLE OF PASSIVE SAFETY SYSTEMS IN PREVENTION AND MITIGATION OF SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS

М. Вишемірський, В. Кравченко. **Роль пасивних систем безпеки в запобіганні та пом'якшенні наслідків важких аварій на АЕС.** Аварія на АЕС Фукусіма Даічі призвела до суттєвого оновлення вимог до безпеки АЕС у всьому світі. Особлива увага приділялася вимогам щодо подолання та управління важкими аваріями як при проектуванні нових енергоблоків АЕС, так і при переоцінці безпеки діючих. Основним результатом переоцінки безпеки діючих енергоблоків була розробка та впровадження технічних засобів і стратегій («FLEX-стратегії») для запобігання та/або пом'якшення наслідків важких аварій. Технічні рішення, які використовуються в сучасних проектах реакторних установок, передбачають декілька варіантів відведення теплоти від активної зони та гермооб'єму окремими системами. Більшість таких систем засновані на пасивних принципах роботи і повністю не вимагають або передбачають мінімальне втручання оперативного персоналу в їх роботу. Водночас реакторні установки, які експлуатуються в Україні, базуються на старих проектах ВВЕР, які не містять пасивних систем безпеки для тривалого відведення тепла від реакторної установки (особливо для випадку повного знеструмлення енергоблоків АЕС, оцінку впливу якого на безпеку АЕС виконано при позачерговій переоцінці безпеки, так званих «стрес-тестах»). Тож в даній роботі проаналізовано доцільність впровадження пасивних систем на АЕС України з ВВЕР-1000 та ВВЕР-440 разом із аналізом існуючих типів пасивних систем та їх поширеністю. За результатами проведеного аналізу визначено доцільність впровадження на АЕС України пасивної системи відводу теплоти від активної зони для ВВЕР-1000 та від конфайнмента для ВВЕР-440. Водночас можливість впровадження таких систем на українських АЕС потребує окремого аналізу. Крім того, надано загальну інформацію про поточний стан оцінки надійності пасивних систем. Адже, незважаючи на те, що надійність пасивних систем безпеки є одним із важливих питань, це питання є малодослідженим і потребує додаткового аналізу.
Ключові слова: АЕС, ВВЕР, важка аварія, пасивна система безпеки, система пасивного відведення тепла, надійність

M. Vyshemirskyi, V. Kravchenko. **Role of passive safety systems in prevention and mitigation of severe accidents at nuclear power plants.** Fukushima Daiichi accidents led to the worldwide update of the NPP safety requirements. Particular attention was paid to severe accidents both during the design of new NPP units and during the safety reassessment of existing ones. Performed safety reassessment of operating units was focused on development and implementation of technical means and strategies directed to prevention and/or mitigation of severe accidents. Technical solutions that are used in modern designs of reactor facilities involve several options for providing of heat removal from the core and containment. Such options include heat removal systems from the reactor core and from the containment of reactor facility. Most of such systems are based on passive principals of operation and do not require or require a minimum action of operating personnel. At the same time, reactor facilities that are operated in Ukraine are based on old VVER designs, which do not include passive safety systems for long-term heat removal (especially for the case of total station blackout, which was in the focus during safety reassessments, so-called "stress tests"). Thus, the necessity of such systems at Ukrainian NPPs with VVER-1000 and VVER-440 was discussed together with analysis of existing types of passive systems and their prevalence. Based on the results of performed analysis the feasibility of implementation at Ukrainian NPPs of a passive heat removal system from the core for VVER-1000 and from the confinement for the VVER-440 was identified. The possibility of implementation of such systems at Ukrainian NPPs requires a separate analysis. In addition, a general information on current state of passive systems reliability assessment was described. It should be noted that despite the reliability of passive safety systems is one of the important issues it is still poorly studied and require additional analyses.
Keywords: NPP, VVER, severe accident, passive safety system, passive heat removal system, reliability

Introduction

The issue of improving safety of nuclear energy has become increasingly relevant after the accidents at nuclear power plants (NPP). Each of them gave a new impetus to research and methodology of safety analysis. The last of the major accidents at Fukushima Daiichi was no exception and led to an update of the NPP safety requirements in the documents of the International Atomic Energy Agency (IAEA) [1], the directives of the European Atomic Energy Community (EURATOM) [2], documents of the Association of Nuclear Safety Regulators of Western Europe (WENRA) [3], etc. Particular attention was paid to severe accidents (SA) both during the design of new NPP units and during the

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safety reassessment of existing ones. The main purpose of such analyzes is the development and implementation of technical means and strategies (so-called FLEX-strategies) to prevent or mitigate the effects of SA.

Implementation of these technical and organizational measures was preceded by a number of targeted NPP safety assessments and development of optimal solutions taking into account the specifics of the NPP unit, site location, climate, possible impacts and damage to NPP elements, available sources of coolant, emergency power supply, etc. [4]. Targeted safety reassessment of Ukrainian NPP power units ("stress-tests") was also performed after the accident at the Fukushima-Daiichi NPP. It was determined that one of the priority strategies to overcome accidents with long-term total station blackout (SBO), which was in the focus after Fukushima-Daiichi accident, is a restoration of heat sink from the primary side. Technical solutions involve several options for providing of heat removal from the core and containment, one of which is a passive heat removal system (PHRS). At the same time, reactor facilities that are operated in Ukraine are based on old VVER designs, which do not include any PHRS. Thus the necessity of such systems at Ukrainian NPPs with VVER-1000 and VVER-440 need to be discussed together with analysis of existing types of passive systems and their prevalence. In addition, despite that reliability of passive safety systems is one of the important issues it is still poorly studied and require additional discussion.

Analysis of related publications

Application of passive safety systems was discussed in the early 90th at the IAEA Conference on "The Safety of Nuclear Power: Strategy for the Future" [5]. As a result, experts from research and design institutes from several countries, that are IAEA members, presented their common views on the PHRS in a document "Balance of passive and active systems for water-cooled evolution reactors" [6]. The main aspects for PHRS design, which should be taken into account, are satisfying the required safety function with sufficient reliability, impact on plant operation, design simplicity and costs of the system. The Safety fundamentals provided in the IAEA document [7] recommends "an appropriate combination of inherent and engineered safety features" for defense in depth. At the same time, requirements for the design of the NPPs provided in the IAEA document [8] propose "following a postulated initiating event, the plant is rendered safe by passive safety features or by the action of safety systems that are continuously operating in the state necessary to control the postulated initiating event".

While a lot of new documents and terms were introduced their discussion and definition was started in the IAEA document [9] in parallel with development of passive systems. Such safety related terms as passive and inherent safety, passive and active system etc. have been widely used when advanced nuclear plants were discussed. Other safety related terms are already described in the IAEA's Nuclear Safety Standards Series (NUSS) and national or international codes and standards. These terms in the codes and standards usually were used for regulatory purposes (namely in relation to present reactor designs). So general idea was to ensure an unambiguous understanding of new terms because many of them (those that were considered in document [9]) have been widely used in countries with operators of NPP without correct understanding of what they mean. The intent of document [9] was not to promote wider use of selected terms, but rather to clarify their meaning. Most of the considered terms can potentially mislead non-specialists and convey to the public undesirable consequences not foreseen by the NPP designers. The criterion for inclusion of each term in document [9] has been whether the term is already in common, widespread use, not whether such use is desirable.

Together with terminology and regulatory requirements the economic aspects related to passive safety systems were analyzed. The use of all passive safety systems (namely accumulators, heat exchangers, and gravity driven safety injection systems) decrease the costs of NPP construction, related to the installation, maintenance and operation of active safety systems that require multiple active elements (such as pumps and/or valves with independent and redundant electric power supplies). As a result, passive safety systems are planned to use in numerous reactor concepts and existing designs (including in Generation III and III+ concepts). Also it is expected that modern passive systems will find applications in the Generation IV reactor concepts, as it was proposed by the International Forum of Generation IV reactors. Another positive aspect in application of passive safety systems is the increasing of the inherent safety of reactor facility by increasing the reliability of its systems [10]. Power reactors which are currently used for electricity production mainly apply a combination of inherent safety characteristics and engineered safety systems, whose operation may be active or passive. The active systems are used much more often and in a larger amount. There have been many proposals for

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applying different technologies in the area of NPP design to reduce dependence on active systems in the past decades. So it was expected than new reactor designs will be much more effective in contribution to improved economics of NPP in terms of construction costs, operation and maintenance costs, ease of operation and reliable equipment and systems.

The differentiation of a passive safety system was proposed in the IAEA document [10], where four categories (A, B, C, D) were established to distinguish the different degrees of passivity. Considering Ukrainian experience in the area of passive system it can be noted, that the only regulatory document, which establishes the concept of "passive system" is "General safety provisions of nuclear power plants" [11]. In addition, some comments on application of passive principles of operation of additional technical means for cooling of nuclear fuel are presented in "Requirements for the systems of emergency nuclear fuel cooling and heat transfer to ultimate heat sink" [12]. Also, in some Ukrainian articles (such as [13]) differentiation of a passive safety systems was proposed, based on document [10]. The main difference is that paper [13] provides more detailer classification of passive systems for of reactor facilities containment. As for the requirements for passive core cooling systems, these requirements are poorly reflected in the regulatory documentation. At the same time, the State Nuclear Regulatory Inspectorate of Ukraine is currently preparing a new updated version of "General safety provisions of nuclear power plants", which will consider the concept of "passive systems" in more detail.

It can be concluded, that systems based on passive principles of operation are mostly applied in advanced nuclear reactors for performing critical safety functions. The spread and the variety of possible safety systems are described in the IAEA document [10]. The levels of actual implementation of safety systems in the reactor designs used for electricity production are very different. The range of maturity of these extend from reactors already in operation to preliminary reactor designs which are not yet submitted for a formal safety review process. Thus, in general, the vast majority of modern reactor designs include passive systems and their implementation into reactor designs and improvement is ongoing in parallel with improvement of regulatory requirements (both globally and in Ukraine).

Purpose and objectives of the study

The main purpose of the study is to assess current degree of implementation of passive safety systems in NPP designs, briefly analyze existing types of PHRS to access the role of passive safety systems in prevention and mitigation of SA at NPPs as well as to identify possible "gaps" related to application of passive safety systems.

Analysis of passive safety systems and their role in prevention and mitigation of SA at NPPs

A new leap in the development of NPP safety requirements led to modernization of existing NPP units. Mentioned modernizations consisted in the implementation of technical and organizational measures, which were developed based on results of targeted NPP safety reassessments. Based on the performed analyses technical means and strategies (so-called FLEX-strategies) were developed and implemented to prevent or mitigate the effects of SA. Implemented technical solutions took into account the specifics of the NPP unit, site location, climate, possible impacts and damage to NPP elements, available sources of coolant, emergency power supply, etc. [4].

Brief description of different types of passive safety systems is collected in the IAEA document [10], which divides all passive safety systems into two groups – passive safety systems for core decay heat removal and passive safety systems for containment cooling and pressure suppression.

Variety of the PHRS, described in [10], include:

– Pre-pressurized core flooding tanks (accumulators). Used in existing NPPs as a part of the emergency core cooling systems. Usually consist of large tanks filled with borated water and pressurized by an inert gas (usually nitrogen). During normal operation these tanks are isolated from the reactor coolant system (RCS) by a series of check valves that are normally held shut by the pressure difference between the RCS and the environment in the tank. Additionally, cut-off valves can be applied for reliable isolation of the accumulators during reactor modes with decreased parameters. In the event of a loss of coolant accident (LOCA), the core pressure will drop below the fill gas pressure. This results in opening the check valves and discharging the borated water into the reactor vessel. Isolation valves should be opened by that moment.

– Elevated tank of natural circulation loops (core make-up tanks). Provide effective core cooling under high coolant pressure. Several advanced reactor designs implement elevated tanks connected to the reactor vessel or primary loop at the top and bottom of the tank. These tanks are filled with borated water to provide coolant injection at system pressure. The tanks are normally isolated from the reactor vessel by an isolation valve located at the discharge line departing from the bottom of the tank itself. The fluid is always sensing full system pressure through the top connection line. During emergency events the isolation valve at the discharge line is opened to complete the natural circulation loop and to permit cold borated water to flow to the core driven by difference of coolant densities in the tank and in the core.

– Elevated gravity drain tanks. Filled with cold borated water these tanks are used under low pressure conditions to flood the core by the force of gravity. In some designs, the volume of water in the tank is sufficiently large to flood the entire reactor cavity. Operation of the system requires opening of the isolation valve and that the driving head of the fluid exceed the system pressure plus with a small additional overpressure required to open the check valves. The effectiveness of the gravity drain tank may be limited under conditions of reactor level decreasing due to steam production in the core region.

– Passively cooled steam generator (SG) natural circulation. Usually are implemented in advanced pressurized water reactor (PWR) designs to remove decay heat passively through the SGs. It is performed by condensing steam generated by the SG inside a heat exchanger submerged in a tank with water or an air cooled heat exchanger (tower). One of the most common type of PHRS in PWR designs.

– Passive residual heat removal heat exchangers. Are implemented into several advanced PWR designs. Their main function is to provide long term decay heat removal by transferring heat via single-phase pressurized heat exchanger with natural circulation. Coolant flow is actuated by opening the isolation valve at the bottom of the PRHR heat exchanger. The PRHR system design is optimized for single-phase liquid heat transfer. Usually it is used for mitigation of the NPP blackout scenario.

– Passively cooled core isolation condensers. Designed for core cooling in a boiling water reactors (BWR) during events with termination of the primary heat sink. During power operations, the reactor is normally isolated from the condenser heat exchanger by closed valves. During events that require core isolation from heat sink, the valves located in the condenser lines are opened and main steam is diverted to the sump heat exchanger where it is condensed in the vertical tube section. The condensate returns to the core by gravity draining inside the tubes.

– Natural circulation sump. Currently used in the designs of reactors, where reactor cavity and other lower containment compartments are used as a reservoir of coolant for core cooling during the loss of coolant accidents. In case of LOCA coolant from the reactor system is collected in the containment sump and when reactor is completely covered with water and the isolation valves are opened. Decay heat removal occurs by boiling in the core. The steam generated in the core goes upward through an automatic depressurization system (ADS) valve that dump steam directly into containment.

Main types of passive safety systems for the containment are [10]:

– Containment pressure suppression pools. Mainly used in BWR designs. Pressure decreasing is performed by bubbling the steam from the leakage through the pool of the coolant. Condensation of the steam prevent containment pressure increasing. Non-condensable gases are dumped through large vent lines submerged in the water in the suppression pools.

– Containment passive heat removal/pressure suppression systems. Uses an elevated pool as a heat sink or air-cooled heat exchangers. Steam vented in the containment will condense on the containment condenser tube surfaces to provide pressure increasing and containment cooling.

– Passive containment spray. System operation is based on steam condensation after contact with the inside surface of the steel containment. Heat is transferred through the containment wall to the external air. An elevated pool situated on top of the containment provides a gravity driven spray of cold water to provide cooling during LOCA.

Mentioned above passive safety systems are included in the designs of the following reactor facilities [10]:

– SWR-1000 (AREVA, France)
– AP 600 and AP 1000 (Westinghouse Electric, USA)
– VVER-640/407 and VVER-1000/392 (Atomenergoproject/Gidropress, Russian Federation)
– Advanced PWR (Mitsubishi, Japan)
– Simplified Boiling Water Reactor (General Electric, USA)
– Advanced BWR (TEPCO, General Electric, Hitachi and Toshiba, Japan)
– Advanced Heavy Water Reactor (Bhabha Atomic Research Centre, India)
– Advanced CANDU Reactor (Atomic Energy of Canada Ltd, Canada) etc.

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Performed analysis showed that passive safety systems are widely spread and included in the designs of the existing and conceptual reactor facilities because of their ability to prevent severe accidents and/or mitigate their consequences.

Reliability of passive safety systems

As PHRS are used under SA conditions their reliability theoretically should be greater than reliability of active systems. It follows from the fact that passive systems rely on natural circulation and do not require any external input or energy for operation. At the same time passive systems may fail not only due to "classical" failure of any mechanical elements but due to deviation of system conditions (thermal hydraulic parameters in the PHRS or parameters in the reactor facility, which affect the course of physical phenomena). Despite the fact that reliability of passive safety systems is one of the important issues it is still poorly studied. General information on first attempts and/or different approaches to assess reliability of passive systems are described shortly in articles [14, 15, 16]. Generally, a few approaches such as reliability methods for passive safety functions (RMPS), reliability evaluation of passive safety system (REPAS), and analysis of passive systems reliability (APSRA) were proposed in the past to evaluate reliability of passive systems. Each of proposed methodologies for assessment of PHRS reliability despite some common approaches has individual advantages, disadvantages and additional issues. One of the main issues – is correctness of application of thermal hydraulic best estimate 1D codes (RELAP5, TRACE, ATHLET etc.). From one side this codes have a long history of their application in the area of NPP safety. But from the other side they were developed for the analysis of processes with forced circulation and their validation on natural circulation phenomena is pretty poor. So the results of thermal hydraulic calculations in the systems with low driving force may not provide realistic evaluation of the system or do not provide necessary accuracy of the calculations. Additionally, mentioned 1D codes cannot reflect complex 3D flow of the convection in the large tanks and pools with heat exchangers, which may affect correct determination of heat transfer coefficients. Also in some PHRS variation of ambient (atmospheric) parameters in time (for instance during day and night time) may affect the effectiveness of the system. Dynamic changing of such parameters is not included into existing methodologies of PHRS reliability assessment. Summing up, it can be noted that existing methods for assessing the reliability of passive systems has number of gaps and/or unsolved issues. Thus it is necessary to develop new method of PHRS reliability assessment or improve existing ones.

Research results

Performed data collection showed that most of modern reactor designs include passive systems, which pay a huge role in prevention or mitigation of severe accidents.

At the same time, reactor facilities that are operated in Ukraine are based on old VVER designs, which did not include PHRS for long-term cooling of the reactor facility. The only passive safety system, which is included into design of Ukrainian NPPs, is a pressurized hydroaccumulators, which inject boric solution into primary side in case of primary pressure decreasing. This provides temporary core cooling in case of loss of coolant accident or allows to extend the time before core damage in case of SBO with actions of operating personal. Also VVER-440 design include system of confinement passive pressure suppression, but this system does not provide heat transfer to the ultimate heat sink, but only accumulate it.

After the accident at the Fukushima-Daiichi NPP Ukraine performed targeted reassessment of safety of Ukrainian NPP power units ("stress-tests"). It was determined that one of the priority strategies to overcome accidents with long-term SBO is the restoration of heat sink from the primary side. Technical solutions involve several options for providing of heat removal from the core. One of them is related to implementation of the mobile equipment, such as mobile pump units (MPU) for SG feeding and mobile diesel-generators of low capacity (MDG). This approach was used by the State Enterprise "National Nuclear Energy Generating Company "Energoatom" (SE "NNEGC "Energoatom")" because of easier and cheaper implementation of such technical means and solutions. Adopted strategy involve depressurization of SG and its feeding by MPU with simultaneous feeding of primary side by emergency core cooling pumps of low capacity.

Effectiveness of such strategy was analyzed in the paper [17]. It was shown that implemented by SE "NNEGC "Energoatom" strategy provide effective core cooling. At the same time in the paper [17] some negative aspects of strategy with SG feeding by MPU were determined. Main of them are recriticality of the core and occurrence of cold overpressure in the primary side. In addition, the success of such actions depends on the timeliness of personnel actions. The results of emergency response drills showed that there is a very small margin of time for connecting the implemented technical means. So in case of any additional unaccounted aspects developed strategy may fail.

Thus, a more preferable solution from the reliability point of view for ensuring heat removal is the implementation of systems that do not depend on the actions of personnel, i.e. passive safety heat removal system (PHRS). But, as mentioned above, old designs of VVER reactors do not include PHRS for long-term heat removal. Therefore, the possibility of their implementation requires separate detailed analysis.

At the same time, for VVER-1000, operated in Ukraine, it is more preferable to analyze the possibility of PHRS implementation for core long-term cooling, which will prevent severe core damage in case of long-term loss of heat removal to the ultimate heat sink (for example, in case of total SBO). Concerning VVER-440, it should be noted that the Ukrainian NPP units with VVER-440 are equipped with an additional emergency feed water system, which should ensure the SG make-up even in case of long-term total SBO. Nevertheless, SE “NNEGC “Energoatom” is planned to implement ex-vessel cooling system at Unit-1,2 of Rivne NPP. Cooling of the reactor vessel will be performed by flooding of the reactor cavity with water, boiling of which on the surface of the reactor vessel will remove decay heat. The core heat will be transferred to the confinement, but the problem of further heat removal from the confinement has not been solved. Thus, for Ukrainian NPPs with VVER-440 it is sensible to analyze possible options for implementing PHRS for long-term cooling of the confinement.

Additionally, it should be noted that despite the fact that reliability of passive safety systems is one of the important issues it is still poorly studied. A few approaches were proposed in the past (see, for instance, articles [14, 15, 16]). Based on the presented information it can be concluded that evaluation of passive system reliability is still a challenging task. It involves not only clear understanding of the operation and failure mechanism of the system, which the designer must do before prediction of its reliability, but still include number of “gaps” and/or unsolved issues. Thus it is necessary to develop new method of PHRS reliability assessment or improve existing ones. Such task has become a subject of discussion, which should also be solved together with analysis of possibility of PHRS implementation at Ukrainian VVER units.

Conclusions

Fukushima Daiichi accidents led to an update of the NPP safety requirements. Particular attention was paid to severe accidents both during the design of new NPP units and during the safety reassessment of existing ones. According to the results of the performed analysis, it was found that passive safety systems are widely spread and included in the designs of the existing and conceptual reactor facilities because of their ability to prevent SA and/or mitigate their consequences. At the same time, reactor facilities that are operated in Ukraine are based on old VVER designs and do not include passive safety systems, which provide long-term cooling in case of ultimate heat sink loss. It was determined that most favorable additional systems, which is expedient to implement at Ukrainian NPPs, are passive heat removal system from the core of VVER-1000 and passive heat removal system from the confinement of VVER-440. The possibility of implementation of mentioned systems at Ukrainian NPPs requires additional analyses. It should also be noted that at the moment the assessment of reliability of passive safety systems is not enough studied. Thus, the development of a methodology and/or criterion for assessing of the reliability of passive safety systems also requires additional research.

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