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EXPERIMENTAL INSTALLATION FOR THE STUDY OF HEAT TRANSFER IN HELIUM ENVIRONMENT DURING DRY STORAGE OF SPENT NUCLEAR FUEL

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The duration and methods of intermediate storage of spent nuclear fuel (SNF) are the subject of constant debate due to economic, licensing and social problems. In this article, the authors present a description of the installation for studying heat transfer in helium environment during dry storage of spent nuclear fuel. Presented a general description of the installation, as well as the planned scenario of the tests that will be carried out.

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INTRODUCTION

Nowadays there are 15 PWR (WWER) units in operation in Ukraine. Historically, Ukraine implemented a scheme for transferring spent fuel to the Russian plants in Ozersk and Zheleznogorsk for reprocessing by chemical extraction of valuable products (plutonium isotopes) for further involvement of these products into the fuel cycle repeatedly. This scheme showed its inefficiency, and in time, it was decided to refuse to export SNF to the Russian Federation and to store fuel in the territory of Ukraine. The first site to stop sending fuel for reprocessing was Zaporizhzhya NPP, which implemented a project to build a dry SNF storage facility in 2001. The interim spent nuclear fuel facility at Zaporizhzhya NPP has operation license for 50 years of storage. The storage facility was designed to store about 9200 Spent Fuel Assemblies (SFAs) in 380 containers. Technology is based on storing SFA in a vertical concrete cask (VSC-24) [1]. Later, a decision was made to build a Centralized Storage Facility for Spent Nuclear Fuel (CSFNF) from VVER reactors in the Exclusion Zone. The construction of the Centralized storage of spent nuclear fuel started in 2015. This facility will apply the technology of Holtec International. Multipurpose Canister (MPC) will be loaded with 31 WWER-1000 SFA or 85 WWER-440 SFA. Using HI-TRAC transfer cask, MPC will be loaded into the HI-STAR transport cask and will be transported horizontally to storage site at Chernobyl exclusion zone by rail. Then, in the cask receiving building, MPC will be loaded into HI-STORM vertical concrete storage system. Storage facility has 100 years operation license. It is planned to store 16529 SFAs in 480 HI-STORM casks at the site [2].

On August 2, 2021, the first loading of SNF took place in the dry storage facility of the Chernobyl NPP. The Interim Spent Nuclear Fuel Dry Storage Facility (ISF-2) is necessary for storing and packing of about 21000 SFA, 2000 spent additional absorbers and more than 23000 extension rods, transported from Chernobyl NPP Units 1, 2, 3 and from "wet" type ISF-1.

Storage technology also based on Holtec International design. Loaded with fuel, Double Wall Canister (DWC) is stored in a horizontal concrete module on the storage site [3].

SNF storage safety is based on five key aspects: ensuring the subcriticality of spent fuel assemblies, compliance with radiation safety standards, not exceeding the allowable storage temperatures of fuel assemblies, ensuring the strength and durability of SNF container structures [4].

Despite the fact that the SNF storage container is a passive system in terms of safety and there have been no serious threats to the safety of personnel environment throughout the history of SNF management, special attention at this stage of nuclear industry development should be paid to studying safety risks at the stage of SNF storage.

There are several reasons for this:

- Continuous growth of spent nuclear fuel;
- Storage facility operational lifetime of 50 years or more;
- Tendency to increase the initial enrichment of fuel assemblies and the burnup.

It is now recognized that extensive computational experiments are required to verify that the storage system design meets the established safety criteria. Calculation tools include CFD (Computational Fluid Dynamics) codes – programs of computational fluid dynamics, software packages based on the Monte-Carlo method to calculate SNF subcriticality, various codes for modeling the process of ionizing radiation transfer to confirm radiation safety [5].

At the same time, the issue of the experimental base and the conduct of full-scale experiments on models under laboratory conditions within the scope of SNF management remains unresolved. In particular, it is important to study the degradation mechanisms of SFAs and container, as well as issues related to normal operation and emergencies.

In the absence of access to work with ionizing radiation sources and given the fact that most of the degradation processes are associated with temperature changes, and the course of emergency scenarios somehow affects the temperature change of the fuel cladding and container structures, the real need is to create experimental facilities to study thermal processes during dry SNF storage.

OVERVIEW OF EXISTING INSTALLATIONS

Taking into account the increasing popularity of using the dry SNF storage method in the world, the countries that are leaders in the development of nuclear technologies are relatively involved in the experimental justification of SFA storage safety in terms of thermal characteristics. Traditionally, the leader in this area is the United States.

As an example, it is worth mentioning a facility for research of thermal conditions of dry storage of boiling reactor fuel on the basis of Sandia National Laboratory. The purpose of this facility is to determine the steady-state temperatures of the stored fuel with different characteristics (enrichment, burnup, storage time in the near-reactor pool) and to confirm the integrity of the fuel assembly during long-term storage. The facility consists of a shell with a 4.57-meter-high stainless-steel tube, inside which a heating element – fuel assembly simulator is installed. Total power of the heating element is 2.5 kW. The helium pressure in the stainless tube varies in the range of 100…700 kPa. Scientists used 150 thermocouples installed at different locations to measure the temperature. The measured parameters were the airflow rate, which cools the outside part of the tube with a heater inside, helium pressure, the maximum temperature of the heating element, and the maximum temperature of the stainless tube. Calculation parameters were Nusselt, Rayleigh and Reynolds numbers [6]. Schematically, the installation is shown in Fig. 1.

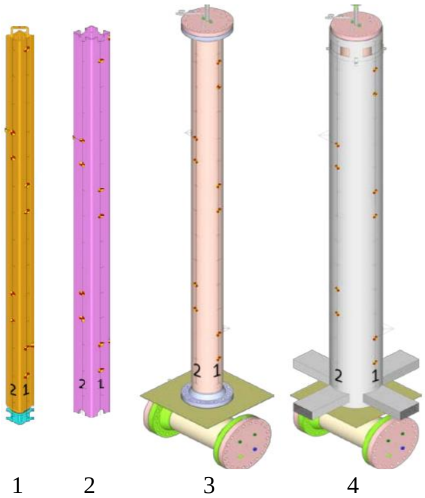

Fig. 1. SNL installation. From left to right: 1 – fuel assembly simulator; 2 – fuel assembly shroud simulator (a structural element of the boiling vessel reactors); 3, 4 – assembled installation with nozzles for helium supply

Another example – the installation by NSE Technology (South Korea), which was created as part of the work of developing a leak detection method for monitoring the integrity of SNF dry storage casks. The main task of the facility was to study thermal processes in vertical dry storage casks, to establish correlation between internal helium pressure, maximum fuel temperature and canister wall temperature. The installation is a 1:3 scale storage container to the real size, with one, mounted in the middle, simulator of fuel assembly. The thermocouples mounted along the height of the simulator at 5 points. The heater's power is 1.7 kW. The helium pressure inside the canister varied in order to simulate leakage in the range of 0…0.46 MPa. The external cooling air temperature was 16 °C. More than 80 calculation experiments carried out on this facility [7]. The scheme of the facility and the photo shown in Fig. 2.

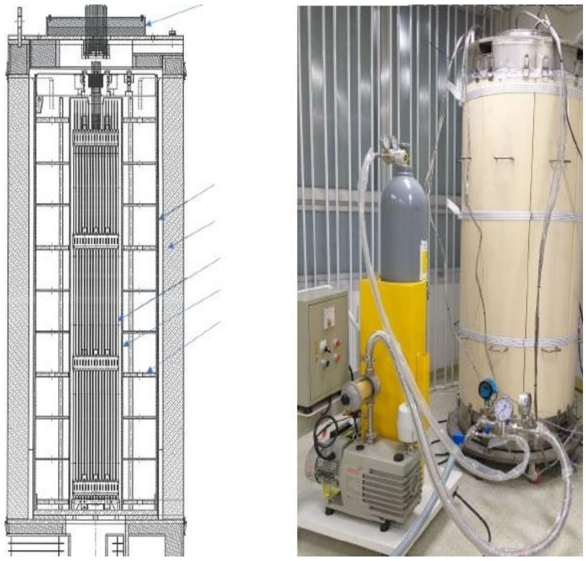

Fig. 2. NSE Technology installation. From left to right: 1 – installation diagram, 2 – general view of the complete installation

PROCESS OF CREATION OF EXPERIMENTAL INSTALLATION

Taking into account significant amounts of spent nuclear fuel unloaded from WWER reactors of Ukrainian NPPs and operational lifetime of ZNPP SF and CSFNF (50 and 100 years respectively) the issues of safety of SNF storage, in particular the issues of integrity of the canister with SFAs over a long period of time are of high importance.

As part of the work on the thesis at the National University "Odessa Polytechnic" in 2020–2021 an experimental installation to study the heat exchange process in the SNF storage container was created. Also, it was developed a program of experiments, including studies of both normal operation conditions and emergency situations.

The materials used to build and operate the installation are the same as those used in the Holtec Intrernational canister.

Installation is a tube with diameter of 85 mm (thickness – 5 mm) made of stainless steel (08KH18N10T), in which the electric heater, heat source (SFA simulator), is placed. At the ends of the tube, there are two flanges: the upper flange is fixed by six bolts M6, the lower flange is welded by argon-arc welding. The height of the assembled installation is 1440 mm. The installation stabilized on a stand for easy access.

The diameter of the upper flange is 115 mm; the thickness in the area of attachment to the tube is 25 mm. On the upper flange, there is a 220 V power supply socket, which also serves as a supporting segment for the heating element. The heater connected to the power supply through a special screw-in contact. On the right side, there is a welded socket for installation of a 16 kgf/cm^2 pressure gauge. On the left, there is a welded socket for an experimental slot (a device, used in experiments, related to helium flow).

Helium, as in a real canister, is necessary to remove heat from the SFA. In our case, it is a heating element. The helium pressure will be set within 7 atm, which corresponds to the technical specification of the Holtec canister.

Valve for helium pressure release is also supposed to be set instead of the slot. General view of the upper part of the installation, namely the upper flange with a branch tube for installation of measuring equipment is shown in Fig. 3.

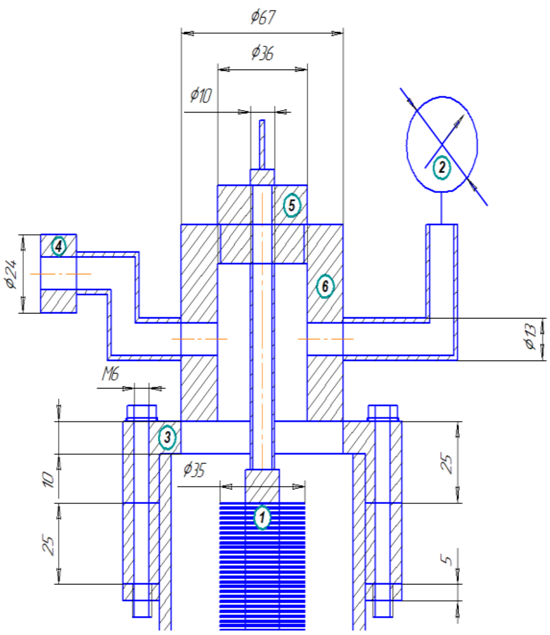

Fig. 3. Upper segment of the experimental setup (longitudinal section):
1 – electric aluminum heater; 2 – manometer;
3 – upper flange (fastened to the tube with bolts M6), 4 - flange for installation of experimental slit;
5 – heater fastening element to the upper part of the flange; 6 – upper part of the flange with branch tube for instruments

The heater is two aluminum tubes with spiral fins connected together. The maximum temperature of the heater is 350 °C and is constant along the entire length of the heater. This simulates the thermophysical conditions of spent nuclear fuel storage inside a steel canister. The temperature will be measured by an infrared portable thermometer along the entire height of the outer wall of the installation.

The bottom segment fixed to the tube by argon-arc welding. The heater installed in the bottom of the lower segment by screwing it into a hole with M12 thread. A reducer attached to the helium inlet in order to change pressure of helium flow. Helium will be supplied through a flexible pipeline from a gas cylinder.

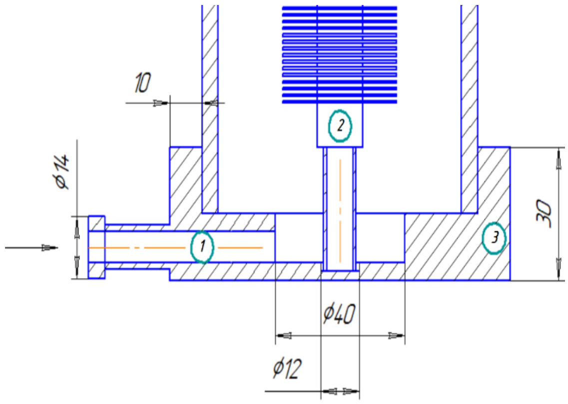

Fig. 4. Lower segment of the experimental setup (longitudinal section):
1 – helium inlet pipe; 2 – heating element (installed in the lower flange); 3 – lower flange

It should be noted, that the unit is easily upgradable and during tests, some design changes are possible as required for specific requirements and test tasks.

EXPECTED TEST SCENARIOS

A steady-state test at a standard pressure planned to determine the benchmark results. First, a pressure of 7 atm and its subsequent retention over a long period of time must be ensured. If there are problems with pressure retention, additional gaskets and seals must be used when assembling the installation. After stable values of pressure and temperature of the outer wall of the tube and when the outside air temperature is established, it is necessary to calculate the heat exchange of free helium convection inside the tube, considering laminar gas flow.

After initial temperature and pressure values are established, several experiments planned in order to calculate the characteristics of heat exchange at different pressure values (75, 50, and 25% of the design pressure). It is also necessary to determine the flow characteristics at different helium concentrations in the tube, to determine the characteristics of laminar flow in the tube. Additionally, it is possible to conduct experiments with different heater power in order to create curves of heat exchange characteristics dependence on parameters of pressure and heater temperature.

It is important to find out the change in the steel temperature, taking into account the possible change in helium pressure, which will help to determine the thermal behavior of the canister material under different cooling conditions.

In order to account emergency scenarios of spent nuclear fuel storage, experiments are planned with a helium leak simulator (a slit of a set diameter), in which a plug with a hole of a few μm will be placed on the upper flange to obtain a stable helium flow from the pipe over a period of time. The above-mentioned characteristics will be calculated, as well as the helium flow rate through the slot in order to determine the dependences of the heat exchange on the helium flow rate.

These experiments will make it possible to determine the peculiarities of helium heat exchange during free convection inside a stainless-steel tube, to establish dependences of heat exchange characteristics on changing parameters (helium pressure, helium flow rate, heater capacity, ambient temperature) in order to identify the main recommendations for increasing thermal safety during storage of spent nuclear fuel.

CONCLUSIONS

This article presented the status of spent nuclear fuel management in Ukraine and described the problem of creating an experimental base to investigate the thermal safety of SNF storage in the world and in Ukraine. Approaches for the creation of experimental facilities and the characteristics and description of existing models in the USA and South Korea were given. The research facility created to study the issues of thermal safety of SNF storage in ONPU was also presented, its key characteristics and parameters were described and shown, a preliminary list of the ongoing research with a description of the expected results was given.

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ЕКСПЕРИМЕНТАЛЬНА УСТАНОВКА ДЛЯ ДОСЛІДЖЕННЯ ПИТАНЬ ТЕПЛООБМІНУ В ГЕЛІЄВОМУ СЕРЕДОВИЩІ ПРИ СУХОМУ ЗБЕРІГАННІ ВІДПРАЦЬОВАНОГО ЯДЕРНОГО ПАЛИВА

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Тривалість та методи проміжного зберігання відпрацьованого ядерного палива (ВЯП) є предметом постійних дискусій через економічні, ліцензійні та соціальні проблеми. У цій статті автори наводять опис стенду для дослідження питання теплообміну в гелієвому середовищі при сухому зберіганні ВЯП. Наведено загальний опис установки, а також планований сценарій випробувань, які будуть проводитися.

ЭКСПЕРИМЕНТАЛЬНАЯ УСТАНОВКА ДЛЯ ИССЛЕДОВАНИЯ ВОПРОСОВ ТЕПЛООБМЕНА В ГЕЛИЕВОЙ СРЕДЕ ПРИ СУХОМ ХРАНЕНИИ ОТРАБОТАННОГО ЯДЕРНОГО ТОПЛИВА

М.В. Яценко, А.В. Королёв

Продолжительность и методы промежуточного хранения отработанного ядерного топлива (ОЯТ) являются предметом постоянных дискуссий из-за экономических, лицензионных и социальных проблем. В этой статье авторы приводят описание стенда для исследования вопроса теплообмена в гелиевой среде при сухом хранении ОЯТ. Представлены общее описание установки, а также планируемый сценарий испытаний, которые будут проводиться.