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Original Article

Thermal analysis of certain accident conditions of dry spent nuclear fuel storage

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ABSTRACT

Thermal analysis of accident conditions is an important problem during safety assessment of the dry spent nuclear fuel storage facilities. Thermal aspects of accident conditions with channel blockage of ventilated storage containers are considered in this article. Analysis of flow structure inside ventilated containers is carried out by numerical simulation. The main mechanisms of heat and mass transfer, which take part in spent nuclear fuel cooling, were detected. Classification of accidents on the basis of their influence on the maximum temperatures inside storage casks is proposed.

1. Introduction

Currently, the problem of spent nuclear fuel (SNF) handling has two solutions: reprocessing and storage (disposal) [1]. The first approach is used in countries with closed nuclear fuel cycles (France, Russian Federation, etc.); the second is used in countries with open nuclear fuel cycles (United States, Ukraine, Sweden, etc.). In any case, SNF is stored a short time before reprocessing or longer before final disposal (depends on accepted nuclear waste management strategy in particular country) [2].

For interim aboveground storage facilities, there are two main ways to store SNF: wet and dry [3,4]. The second is the most widely used strategy, with different types of storage (modular, cask, containers, etc.). One popular type of storage facility is based on usage of ventilated containers with a passive ventilation system. This type of storage equipment uses the principal of natural convection for heat removal and does not require additional engines or electrical systems for cooling [4]. In this article, as an investigated object, a ventilated storage container for SNF will be considered.

Many investigations have been completed in the field of thermal analysis of storage container accident conditions [5–9]. According to International Atomic Energy Agency (IAEA) requirements, the traditional approach is to consider fire accidents [5,6], very low ambient temperatures [7], and full blockage of ventilating channels [8]. A literature review has shown that for cooling improvement at accident conditions, authors have usually proposed to use external ribs or similar structures and, generally, have not paid enough attention to analysis of ventilation duct work and to the identification of factors that influence thermal processes. In consideration of ventilation duct blockage (types of accidents that should be investigated, according to IAEA requirements, during safety assessment of SNF storage facility), only full (100%) or half (50%) blockages of ventilation ducts are analyzed [8,10–12]. The first case, of course, is the most dangerous, because it involves a total stop of one of the most effective thermal removal mechanisms, which lies at the base of the container cooling system—convection. With the second case (half (50%) blockage), in the author's opinion, some problems exist. This type of accident can happen with higher probability than full blockage, so it should be considered more carefully. After analyzing existing studies of under 50% of blockage, usually, authors have come to understand the blockage of inlet vents [for example, 8, 12] and have focused their investigations on the stopping of the cooling airflow rate. At the same time, there have been no investigations of full outlet vent blockage under accidents with partial blockage of ventilation ducts. Also, other cases, such as blockages of 25%, 75%, etc., are not considered in the literature because of the statement that thermal consequences of these blockages will be less than those at full blockage. However, classification of vent blockage types by criterion of maximum temperature inside storage cask and detailed information about thermal processes and temperatures of containers elements could be used in the stage of ventilating container development. Classification of blockage accidents, along with results of transient analysis, could

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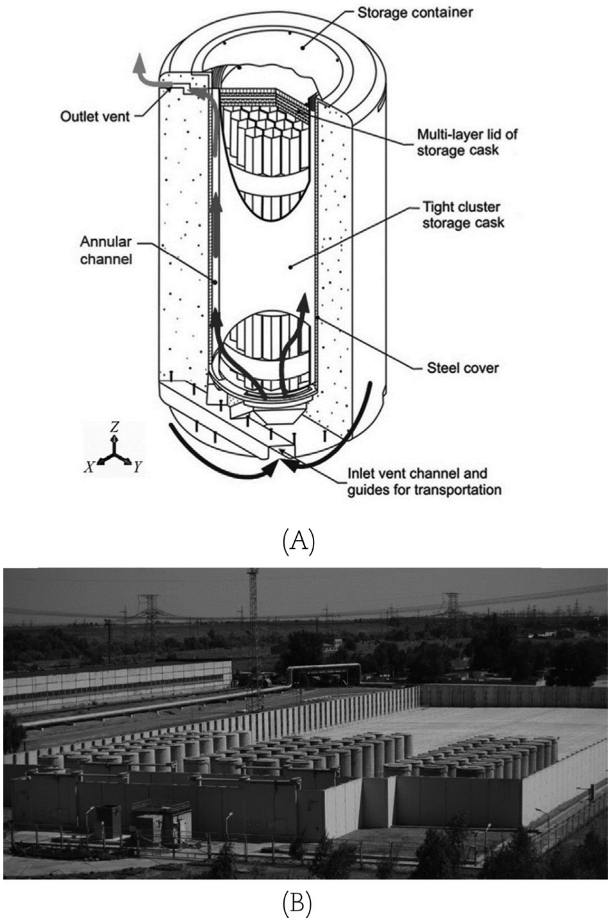

(A)

(B)

Fig. 1. Zaporizhska NPP. (A) Storage container. (B) Dry. SNF storage facility. SNF, spent nuclear fuel.

be used in the development of elimination actions of accidents results (for example, which channels must be cleared/opened first).

The goal of this article is to detect the main heat removal mechanism in ventilated SNF storage containers and the flow structure of cooling air in ventilation ducts, through simulation of the thermal and gas dynamics processes that take place during accidents with ventilation duct blockage. On the basis of the obtained results, it will be possible to classify accident conditions by taking into account their thermal consequences and use this information for the development of effective prevention actions or actions to eliminate possible accident consequences.

2. Problem definition

In this article, the ventilated container that has been used in the dry SNF storage facility at the Zaporizhska Nuclear Power Plant (NPP) since 2001 is considered. The structure (Fig. 1) and main geometrical parameters (Table 1) of the container are presented below. A hermetic cask with 24 spent fuel assemblies from reactor WWER-1000 is placed in a concrete container. This type of container (prototype is container VSC-24 of the Sierra Nuclear Corporation) uses natural convection for SNF cooling. Ambient air comes through bottom inlet channels, removes heat from the hermetic cask with spent fuel assemblies, and passes out through top outlet vents.

Table 1
Geometrical parameters of the container.

Parameter	Value
Fuel assembly	
Shape	Hexahedron
Number of fuel rods	312
Length	3.837 m
Storage cask	
Number of spent fuel assemblies	24
Height	4.973 m
Diameter	1.715 m
Inner medium	Helium
Pressure inside	1 atm.
Container	
Height	5.809 m
Diameter	3.378 m
Width of annular channel	0.07 m

All simulations were carried out for a single container placed on an open storage platform; the average summer temperature +24°C and calm conditions are assumed. The heat generation of all spent fuel assemblies is 24 kW (maximal allowable heat generation for this type of container) [13]. Insolation was not considered.

Safety criteria limit maximum temperatures of fuel inside storage cask to 350°C for long storage in helium and up to 450°C for short periods (up to 8 h) such as during extreme weather conditions and transportation.

3. Methodology

For containers with SNF, which are characterized by high radioactivity, it is not possible to perform natural experiments; therefore, only numerical simulation could be carried out. Conjugate heat transfer problems allow numerical simulation of mutual heat transfer in solids and fluids while taking account of basic principles of gas dynamics. Therefore, this type of problem is effective for thermal process simulation at the dry storage of SNF. A mathematical model to solve the above described problem includes [14] the following:

—continuity equation

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)+\frac{\partial}{\partial z}(\rho w)=0,$$

where u, v, w are Cartesian components of velocity vector; ρ is gas (air) density;

—equation of motion of viscous gas

$$\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial x}+\rho w\frac{\partial u}{\partial x}=-\frac{\partial p}{\partial x}+2\frac{\partial}{\partial x}\left(\mu_{ef}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{ef}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+\frac{\partial}{\partial z}\left(\mu_{ef}\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right)-\frac{2}{3}\frac{\partial}{\partial x}\left(\mu_{ef}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right),$$

$$\rho u\frac{\partial v}{\partial x}+\rho v\frac{\partial v}{\partial x}+\rho w\frac{\partial v}{\partial x}=-\frac{\partial p}{\partial y}+2\frac{\partial}{\partial y}\left(\mu_{ef}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial x}\left(\mu_{ef}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+\frac{\partial}{\partial z}\left(\mu_{ef}\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)\right)-\frac{2}{3}\frac{\partial}{\partial y}\left(\mu_{ef}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right),$$

$$\rho u\frac{\partial w}{\partial x}+\rho v\frac{\partial w}{\partial x}+\rho w\frac{\partial w}{\partial x}=-\rho g-\frac{\partial p}{\partial z}+2\frac{\partial}{\partial z}\left(\mu_{ef}\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial x}\left(\mu_{ef}\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right)+\frac{\partial}{\partial y}\left(\mu_{ef}\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right)-\frac{2}{3}\frac{\partial}{\partial z}\left(\mu_{ef}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right),$$

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