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Preliminary Design for a Dual Purpose Cask Containing 12, 18, or 19 Spent Fuel Assemblies of Bushehr Nuclear Power Plant

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Abstract

The Bushehr nuclear power plant with annual spent fuel production of 21 tons of heavy metals is under commercial operation since 2013. A recently developed dual purpose cask for the dry interim storage and transportation of the spent fuel assemblies of Bushehr nuclear power plant are presented. To design of the fuel basket, materials of borated steel and borated aluminum (BORAL) with different boron content were considered. For the external neutron shielding of the DPC, solid materials such as borated polyethylene were taken into account instead of liquid ones such as ethylene glycol mixed with water.

Introduction

Bushehr Nuclear Power Plant (NPP) is a WWER 1000 type pressurized water reactor (model V-460). The unit No. 1 of the plant is under commercial operation since 2013 [1]. The reactor core consists of 163 fuel assemblies which is made up of 311 fuel rods within the framework consisting of 15 spacing grids, 1 central tube, 18 guiding channels, 1 tube for in core instrumentation detectors (ICID), and supporting lower grid. The maximum burnup of the fuel in one assembly is about 49 MWday/kgU. The fuel assembly and fuel rod of the Bushehr NPP are illustrated in Figure 1 [2]. In addition, the main specifications of the Bushehr NPP fuels are presented in Table 1 [2].

Annual spent fuel production of the Bushehr NPP is about twenty one tons of heavy metals. The spent fuel assemblies will be stored at least for three years in the spent fuel pool next to the reactor core. The capacity of the pool for safe storage of the spent fuel assemblies is sufficient for about eight years [2]. After this cooling time, the old spent fuel assemblies shall be removed from the pool to provide enough capacity for the new ones. As a result, interim storage of the spent fuel assemblies outside of the reactor building (at least for short time) is unavoidable for any option which will be chosen later as an endpoint of spent fuel management.

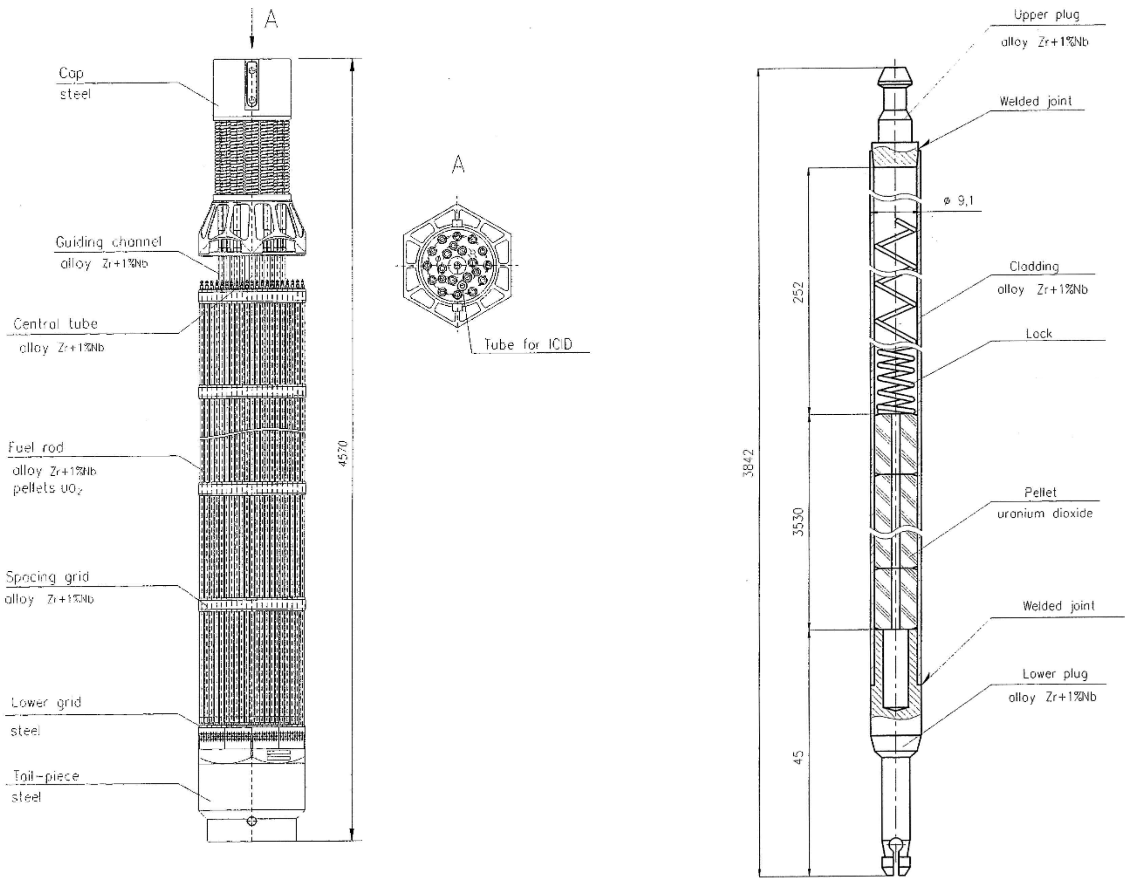

Figure 1 Fuel assembly and fuel rod used in the Bushehr NPP

Table 1 Main specifications of Bushehr NPP fuels

Parameter		**Value / Specification**
Reactor	Reactor type	WWER 1000 (V-446)
Fuel assembly	Geometry	Hexahedral prism
	Maximum dimension for wrench, cm	23.51
	Height, m	4.570
	Fuel (UO_2) mass, kg	489.8
Fuel enrichment	Type 16, Average ^{235}U wt%	1.6
	Type 24, Average ^{235}U wt%	2.4
	Type 36, Average ^{235}U wt%	3.62
	Type 40, Average ^{235}U wt%	4.02
Fuel rods	Number of fuel rods	311
	Clad inside diameter, mm	7.73
	Clad outside diameter, mm	9.1
	Clad material	Alloy Zr+1%Nb
	Active fuel length, m	3.53

Spent Fuel Management

A variety of wet and dry interim storage facilities are operating around the world. However, a review of spent fuel storage facilities implemented during the last decade shows that the storage in a dry environment is becoming a prominent alternative, especially for newly built facilities [3]. The main attractions of dry storage are its safety due to passive cooling capability, minimized operational costs by the passive cooling features, and the ability to add incremental capacity [3, 4, and 5]. Moreover, the Fukushima nuclear accident of March 2011 dramatically revealed the potential risks of holding significant spent nuclear fuel at wet pools requiring continuous water circulation to maintain safe cooling [6].

Dry storage systems started to be developed in the late 1970s and early 1980s [7]. As the demand for additional spent fuel storage is began increasing in the 1980s, cask technology has begun to be applied in the dry storage and transport service for spent nuclear fuels. This has resulted in the development of dual purpose casks (DPCs) [3]. Demands are continuously increasing owing to various advantages such as easy system installation, expandability, transportability, economic efficiency, safety, and public acceptance [8].

Conventionally, the TK-13 cask which is a forged stainless steel flask, is utilized to transport twelve assemblies from the spent fuel pool of WWER 1000 reactors [9]. The transportation systems by use of TK-13 cask for these reactors were developed in the 1983-1991 period [3]. In view of global trends, this system is going to be replaced with dual purpose ones. According to the site requirements such as crane capacity and cask compartment dimensions, there are some design limitations for new casks. Therefore, the weight, diameter, and height of these casks for Bushehr NPP shall not exceed 120 tones, 2.5 meters, and 6 meters, respectively.

The design of a DPC is strictly related to the need to protect the population and environment from exposure to the radiation emitted by the radioactive materials contained in the spent fuel assemblies [10]. The main requirements for a DPC are containment of radioactivity with airtight barriers, biological shielding, and decay heat removal (cooling) as well as to ensure that spent fuels remain subcritical which means that they cannot accidentally undergo a nuclear fission reaction (criticality control) [10, 11]. These requirements shall be satisfied during service life of the DPC which generally is about several decades.

Dual Purpose Cask Preliminary Design

Preliminary concept of a DPC for Bushehr NPP is shown in Figure 2. The main design principles of the DPC are use of forged carbon steel as the main body and gamma shield, use of solid materials such as borated polyethylene as the neutron shield instead of liquid ones (ethylene glycol mixed with water) which is common for the TK-13, and use of two closure lids for sealing.

In addition to the national regulations, the requirements and acceptance criteria for design of the DPC are based on International Atomic Energy Agency (IAEA) Safety Standards for transportation and storage of spent fuels. For instance, the 9 meter drop, puncture, and 30 min fire tests provided by IAEA transport regulations (SSR-6) are settled as the hypothetical accident conditions.

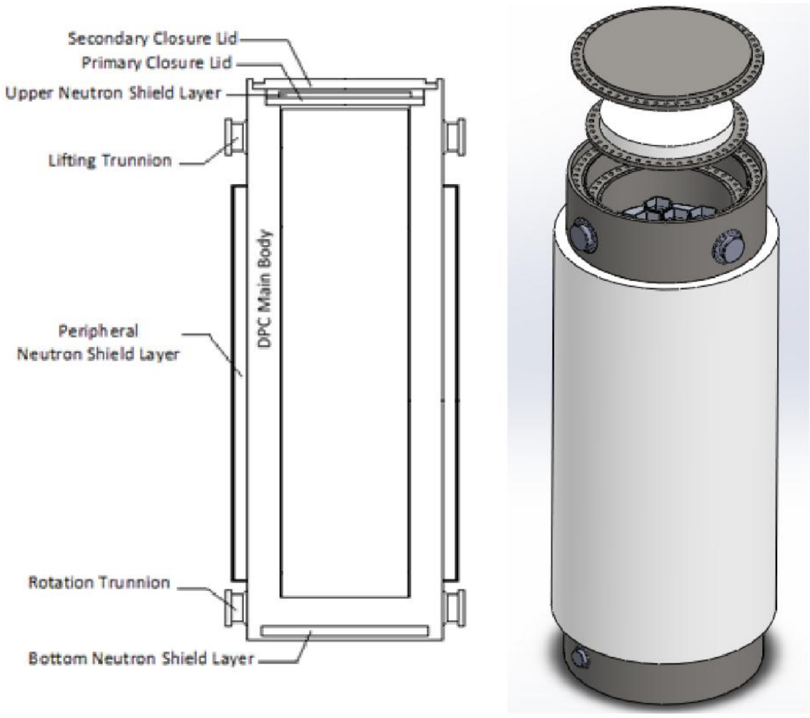

Figure 2 Preliminary concept of the DPC for Bushehr NPP

According to the assembly geometry of the Bushehr NPP fuels and design limitation of the cask (maximum diameter up to 2.5 meters), the capacity of 12, 18, or 19 spent fuel assemblies is conceivable. As a result, the criticality calculations were performed for 12, 18 and 19 fuel assemblies (Figure 3). Materials of borated stainless steel and borated aluminium (BORAL) with different boron content were considered for the basket.

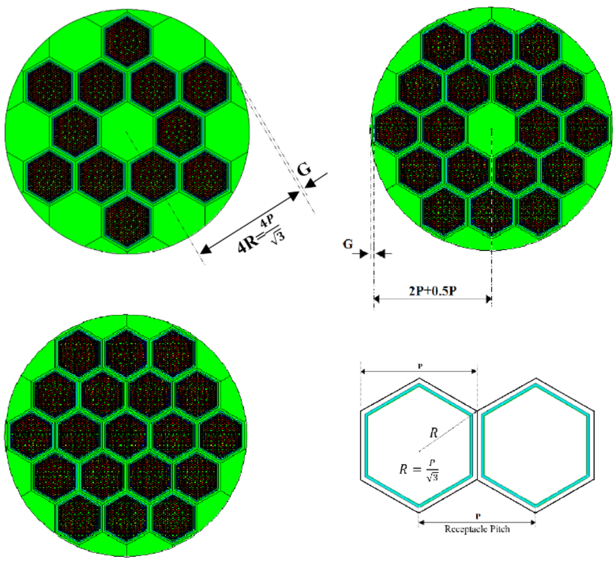

Figure 3 Arrangement of 12, 18, and 19 fuel assemblies in the basket of the DPC

In view point of criticality safety, the DPC shall be so designed that the effective multiplication factor (k_{eff}) of the most reactive configuration, including all biases and uncertainties, be maintained below the maximum upper subcritical limit (USL). The effective multiplication factor of the DPC could be controlled by material, boron content, and receptacle pitch of the basket (Figure 3). Several criticality calculations were provided for different material, boron content, and receptacle pitch of the DPC basket containing 12, 18, or 19 spent fuel assemblies of Bushehr NPP. Some calculated k_{eff} for different basket materials and boron content are presented in Table 2. By use of the results of criticality calculations, the minimum required receptacle pitch and consequently minimum basket diameter was determined. It is necessary to mention that the calculated USL was 0.93127.

Table 2 Calculated k_{eff} for different basket materials

DPC Capacity	Basket Material	Boron Content	Min. Required Receptacle Pitch (Basket Diameter)	k_{eff} of the Most Reactive Config.
12 Spent Fuel Assemblies	Borated Stainless Steel	1.1 wt%	28.5 cm (134.3 cm)	0.9294
		2.5 wt%	28 cm (132 cm)	0.91583
	Borated Aluminum (BORAL)	7 wt%	27.5 cm (129.7 cm)	0.91759
		17 wt%	26.5 cm (125 cm)	0.92121
18 Spent Fuel Assemblies	Borated Stainless Steel	1.17 wt%	30 cm (152.6 cm)	0.92935
		2.5 wt%	29 cm (147.6 cm)	0.92913
	Borated Aluminum (BORAL)	7 wt%	29 cm (147.6 cm)	0.91862
		17 wt%	28 cm (142.6)	0.91455
19 Spent Fuel Assemblies	Borated Stainless Steel	1.17 wt%	31 cm (157.6 cm)	0.91841
		2.5 wt%	30 cm (152.6 cm)	0.91534
	Borated Aluminum (BORAL)	7 wt%	29.5 cm (150.1 cm)	0.92214
		17 wt%	28.5 cm (145.1 cm)	0.91687

Based on the spent fuel activities (photon and neutron release rates), the basket diameter (Table 2), and shielding calculations, the minimum DPC diameter could be determined in each case. According to the IAEA transport regulations, the radiation level under routine conditions shall not exceed 2 mSv/h at any point on, and 0.1 mSv/h at 2 m from, the external surface of the cask. For the external neutron shielding of the DPC, solid materials such as borated polyethylene were taken into account. The specification of the materials used in the shielding calculations is presented in Table 3.

Table 3 Specification of neutron shield materials considered in this study

Material	Density (g/cm^3)	Chemical Composition (wt%)
Polyethylene	0.93	H (14.4), C (85.6)
Borated Polyethylene	1.00	H (12.5), C(77.5), B(10.0)

Conclusion

To dry interim storage and transport of the spent fuels of Bushehr NPP, dual purpose cask system can be utilized. In this paper, a recently developed DPC for this purpose is presented. The main body of the proposed DPC is forged carbon steel. For the preliminary design calculations of the basket, materials of borated steel and borated aluminum (BORAL) with different boron content were considered. In addition, the neutron shielding materials of polyethylene and borated polyethylene were taken into account.

Based on the criticality and shielding calculations, main characteristics of the DPC such as the cavity diameter, the DPC diameter, and minimum weight of the DPC could be determined. The technical data of the DPC for some of the main cases are summarized in Table 4.

Table 4 Main characteristics of the DPC for Bushehr NPP fuels

Parameter		Specification
Fuel Specifications	Assembly Type	WWER 1000
	Maximum Initial ^{235}U Enrichment	4.1 wt%
	Maximum Photon Release Rate per Assembly	2×10^{16} Photon/sec
	Maximum Neutron Release Rate per Assembly	7×10^{8} n/sec
DPC Capacity of 12 Spent Fuel Assemblies	Minimum Height	5.65 meters
	Cavity Diameter	1.32 meters
	Minimum Diameter	2.25 meters
	Minimum Weight (unload)	89 tons
DPC Capacity of 18 Spent Fuel Assemblies	Minimum Total Height	5.65 meters
	Cavity Diameter	1.48 meters
	Minimum Diameter	2.41 meters
	Minimum Weight (unload)	96 tons
DPC Capacity of 19 Spent Fuel Assemblies	Minimum Total Height	5.65 meters
	Cavity Diameter	1.53 meters
	Minimum Diameter	2.46 meters
	Minimum Weight (unload)	100 tons

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