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Preliminary analysis of an integral Small Modular Reactor operating in a submerged containment

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ABSTRACT

This work addresses the conceptual design of a submerged nuclear power plant, where a horizontal cylindrical hull, placed on the floor of a sea or an artificial lake, hosts an integral pressurized Small Modular Reactor (SMR). A scaled version of the International Reactor Innovative and Secure (IRIS) that matches the requirements of the submerged containment is here proposed, providing a preliminary sizing of the primary components. Based on the presence of a large water reservoir (sea or lake) acting as a permanent heat sink, a basic fully passive safety strategy has been developed and its principles have been investigated, by means of the numerical simulation of a Station Black-Out (SBO) scenario. The outcomes show that natural circulation flows in the primary circuit and in the Emergency Heat Removal System (EHRS) can provide a very effective heat transfer capability from the fuel rods to the external water. The submerged reactor design owns very interesting safety features, which inherently prevent from the Fukushima-like scenarios, i.e. Loss Of Offsite Power (LOOP) and a Loss of Ultimate Heat Sink (LUHS), thus representing a noticeable improvement for a next generation nuclear reactor. However, some critical issues for the deployment of such a concept are also identified and briefly discussed.

1. Introduction

Emergency cooling during Fukushima Daiichi nuclear accident failed because of the loss of on-site/off-site electrical power and the consequent lack of a heat sink. The accident has emphasized that current nuclear power plants may show strong difficulties in facing prolonged Station Black-Out (SBO) scenarios. The response of nuclear industry to this event included a renovated attention to the development of passive safety systems for new designs (International Atomic Energy Agency, 2016a). Passive systems own the potential to improve the safety of nuclear power plants, as well as to simplify the layout and to reduce the costs. After Fukushima, guaranteeing an adequate core cooling through natural circulation for a very long grace period, without electrical input or human intervention, has become an important feature for the safety strategy of some Gen III + designs. During the last three decades, those requirements have stimulated large efforts among researchers in nuclear thermal-hydraulics, aimed at understanding the physics and predicting the transient evolution of natural circulation and multiphase flow. These efforts are currently going on to support the design of safer, cheaper and sustainable nuclear reactors. Submerged Small Modular Reactors (SMRs) can potentially address this challenge. Nowadays they are mainly at conceptual design level, but their development could provide a great technological advancement in the nuclear industry. Those nuclear reactors operate in a containment moored on the floor of a sea or an artificial lake (Fig. 1) and the power generated is transferred to the land. This concept offers unique safety features in terms of enhanced protection towards Fukushima-like accident scenarios, i.e., Loss Of Off-site Power (LOOP) and Loss of Ultimate Heat Sink (LUHS), as well as other critical scenarios, including Loss Of Coolant Accident (LOCA), and external events, e.g., flooding, tsunami and malevolent human actions.

In the framework of the development of innovative reactor designs, the submerged SMR concept has obtained a certain attention in recent years. Early projects were presented by Electric Boat (General Dynamics Electric Boat Division, 1971) and Herring (1993) in the 1970's and 1990's respectively. The recent progress in subsea oil&gas technologies, in submarine cables for offshore renewables and in shipbuilding techniques, makes offshore power reactors more feasible today than before, with an increasing interest towards this option (Buongiorno et al., 2016).

In 2014, the French company DCNS (now Naval Group) presented the Flexblue concept (Haratyk et al., 2014), a subsea and fully transportable modular power unit that supplies 160 MW_{el} to the grid via submarine cables. Flexblue adopted pressurized water reactor technology and the projects was aimed at implementing several enhanced passive safety features, to exploit the seawater as a permanent heat sink

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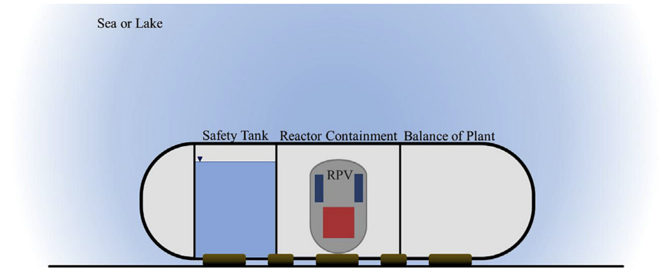

Fig. 1. Concept of a submerged SMR

and ensure an unlimited grace period in case of accident. In addition, Flexblue can offer other advantages in terms of manufacturing and possibility to reach isolated sites. Some analyses about core design and safety strategy of Flexblue are available in open literature (Ingremeau and Cordiez, 2015) (Santinello et al., 2017a) (Haratyk and Gourmel, 2015) (Gourmel et al., 2016), but important issues concerning the reactor design and safety systems are still under development. In particular, although pressurized water is undoubtedly the most reliable technology for such a concept, Flexblue still does not present a final reactor layout. Two solutions were under consideration, but a thorough investigation about their capability to achieve design and safety targets has not yet been addressed. As a first option, DCNS used a VVER-type design for preliminary safety analyses (Haratyk and Gourmel, 2015) (Gourmel et al., 2016). Thanks to the horizontal U-tube Steam Generator (SG), the total height of the reactor does not exceed the diameter of Flexblue hull (14 m), but such solution does not provide compactness to the primary system. Moreover, the horizontal layout of the SGs does not facilitate a natural circulation regime during emergency cooling. A second option proposed by CEA is the SCOR-F concept (NUSMoR, 2014), a reduced power version of the 600 MW_{el} Simple COmpact Reactor (SCOR). It consists of a pressurized reactor with a vertical U-tube steam generator placed right on top of the core. This layout seems not suitable to minimize the global height of the reactor and to fit the containment. A work by Shirvan et al. (2016) examined five nuclear technologies in relation to their adaptability for an offshore underwater SMR: Lead-Bismuth Fast Reactor (LBFR), Organic Cooled Reactor (OCR), Superheated Water Reactor (SWR), Boiling Water Reactor (BWR) and integral PWR. They concluded that all these technologies are good for a fully passive safety strategy. However, LBFR and OCR, which are identified as the most suitable technologies, can rely on a very little experience in civil nuclear industry, therefore achieving a complete reactor design and meeting the requirement of safety authorities would be very difficult and not feasible in the short-medium term.

The present work introduces the concept of an integral PWR (iPWR) SMR, suitable to operate in a submerged containment and based on a scaled version of the International Reactor Innovative and Secure (IRIS) (Carelli et al., 2004) (Petrovic et al., 2012). IRIS is an integral, modular, medium size (335 MW_{el}) PWR, based on passive safety systems and a pressure suppression, steel containment. The new proposal is aimed at obtaining a reactor layout able to satisfy design and layout constraints as well as safety requirements. The primary components have been revisited in order to reduce the electrical output to 160 MW_{el} and the reactor height below 14 m (Section 2), providing a preliminary sizing and thus letting define a basic safety strategy (Section 3). Then, the resulting preliminary design has been tested in a numerical simulation of a SBO scenario (Section 4), where the secondary side of the steam generator is connected to an emergency condenser immersed in the external seawater. The simulations put on evidence the potentiality that such conceptual design can offer in term of enhanced safety features. However, many challenges about the deployment of a submerged SMR still remain open: these are identified and briefly discussed in Section 5.

2. Revisited reactor layout: IRIS-160

2.1. Overview

Scaling the IRIS design is not a new operation: in 2009 Petrovic et al. (2009) proposed the concept of IRIS-50, a reduced power (50 MW_{el}) version of the reference IRIS design, conceived to better address cogeneration purposes and to supply electricity to remote or isolated areas. However, in the present case the constraints and the requirements are considerably different. The primary limitation for the design of a submerged SMR is given by the diameter of the horizontal cylindrical containment. Based on construction capacity and feasibility end economics considerations, DCNS proposed a 14-m diameter hull (Haratyk et al., 2014) for the Flexblue case. That value is assumed as reference for this work. Another constraint is the heat transfer capability of the hull during emergency operation, which identifies the power output of the reactor. Santinello et al. (2017a) investigated that capability with a CFD study and found that the decay power of a 500 MW_{th} (roughly 160 MW_{el}) reactor could be rejected through the containment. Thus, that value is assumed for a scaled IRIS-160 version. Reactor scaling mainly consists of revisiting the design of primary components, i.e. reactor core, control rods driving mechanism, steam generator, primary pumps and pressurizer.

2.2. Reactor core

Reactor core design considers a standard PWR fuel assembly as adopted in IRIS: a configuration made of 89 fuel assemblies with 264 fuel rods in a 17 × 17 square array. The resulting diameter of the core is around 2.75 m. The active height of the fuel elements has been scaled down to reduce the power output: the active height of IRIS-160 fuel element must be roughly halved with respect to the 4.20 m fuel assembly height adopted in IRIS. Among the current or proposed offer of fuel elements, some products seem to be suitable for the purpose, e.g. Framatome, Lo-Lopar, M-Power and Westinghouse SMR, all with active height around 2.5 m (Nuclear Engineering International (NEI), 2014). The active height of NuScale and Smart reactors is 2 m and CAREM-25 adopts 1.4 m height elements (International Atomic Energy Agency, 2016b), although these reactors are designed with power output smaller than IRIS-160. In principle, a 2-m value for the fuel assembly active height can be reasonably assumed. Considering gas plenum and core support plates, the overall height of IRIS-160 core would be in the range of 3.00–3.20 m. Albeit neutronic verification must be performed to assess the of such a core, the solution seems feasible.

2.3. Control rods driving mechanism

An integral reactor allows placing the Control Rods Driving Mechanism (CRDM) inside the Reactor Pressure Vessel (RPV). This carries two advantages: (i) the rod ejection accident is eliminated by design, because there is no differential pressure to drive out the CRDM extension shafts; (ii) there are no nozzle penetrations on the upper head of the RPV. In IRIS design, the CRDM was placed above the core and actuated with electromagnetic or hydraulic mechanism. For IRIS-160, a similar approach is maintained. The height of the CRDM is roughly twice the total length of the fuel assembly, to host the withdrawn control rods and the drive line, plus the height of the handling mechanism. The overall height can be estimated between 5.5 and 6.0 m.

2.4. Steam generator

The Steam Generator (SG) design for IRIS-160 has undergone large modifications with respect to the IRIS original design. In IRIS, eight helical coil SG modules were placed around the barrel, with module diameter equal to 1.5 m. Such solution is not feasible for IRIS-160: due to the reactor size reduction, for economic reasons it is desirable to