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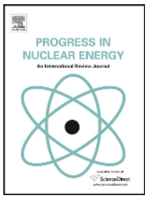

Preliminary analysis of an integral Small Modular Reactor operating in a submerged containment

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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).

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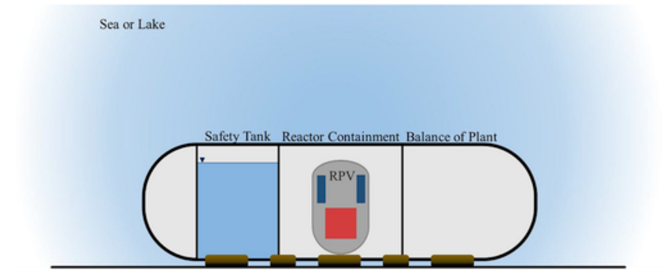


Fig. 1. Concept of a submerged SMR

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 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 reduce also the vessel diameter. Therefore, a layout with two or four helical SG modules co-axial to the barrel is proposed. Two constraints have been imposed: a restriction on the length of each helical tube of 32 m (due to manufacturing reasons, same for IRIS) and the SG module height, limited to 4 m since there must be room for headers and pumps within the limit of the CRDMs clearance. For a preliminary design, the same tube diameter and pitches adopted in IRIS have been maintained. Main geometrical parameters are given in Table 1. The resulting SG module outer diameter as a function of the number of tube rows is given in Fig. 2. For each number of rows and depending on the number of modules, the optimized average length of tubes has been calculated.

The preliminary sizing has been performed with a Lumped Parameter Approach (LPA) and then verified with a Relap5 simulation. Two configurations, i.e. 2 SG modules (4 headers) and 4 SG modules (8 headers), have been considered. The sizing calculations aim at determining the heat exchange surface, and consequently the number of tubes and rows, needed to transfer the thermal power (500 $\mathrm{MW_{th}}$) from the primary to the secondary side. LPA employs energy balances, Newton's law of cooling and empirical correlations for heat transfer coefficients. Primary fluid flows down across the tube bundle, while steam is produced and superheated inside the helically coiled tubes. Since the thermal power of the scaled version is roughly halved with respect to standard IRIS value, on the primary side two options are possible: the SG inlet specific enthalpy and (a) the SG outlet specific enthalpy, or alternatively (b) the total mass flow rate can be maintained equal to those adopted in IRIS. Consequently, suitable outlet values satisfying the energy balance must be taken for (a) the total mass flow rate or (b) for the outlet specific enthalpy, respectively. The advantage of choice (a) is a dramatic reduction of pressure losses on the primary side due to the decrease of the total mass flow rate, while choice (b) represents the best solution to maximize the temperature difference between primary and secondary fluid and therefore to enhance the heat transfer process. Both alternatives are analyzed. As far as secondary side flow rate is concerned, it has been reduced in order to obtain superheated steam at outlet, with the same specific enthalpy of the standard IRIS. The same primary and secondary operating pressures of IRIS, i.e. 15.5 and 6.2 MPa respectively, have been considered.

Table 1
SG geometrical parameters.

Tube outer diameter	17.46 mm
Tube thickness	2.11 mm
Vertical pitch	23.00 mm
Horizontal pitch	23.85 mm
Barrel outer diameter[a]	2.85 m

[a] Corresponding to SG module inner diameter.

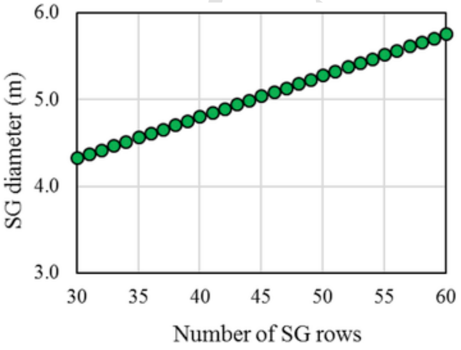


Fig. 2. SG diameter given the number of rows.

To take into account the different heat transfer regimes of secondary side two-phase flow, the tube has been divided into four zones: (i) subcooled liquid, (ii) bulk boiling, (iii) CHF and post dryout, (iv) superheated steam. The heat transfer problem in each zone is solved by means of the electrical analogy, considering primary and secondary convective resistances, plus the conductive resistance for cylindrical geometry accounting for the tube wall. Based on Newton's law of cooling, the following system can be written for each zone:

$$\begin{bmatrix} \frac{1}{R_w} & -\left(\frac{1}{R_w}+\frac{1}{R^{II}}\right) \\ -\left(\frac{1}{R_w}+\frac{1}{R^{I}}\right) & \frac{1}{R_w} \end{bmatrix} \begin{bmatrix} T_w{}^{I} \\ T_w{}^{II} \end{bmatrix} = \begin{bmatrix} -\frac{T_b{}^{II}}{R^{II}} \\ -\frac{T_b{}^{I}}{R^{I}} \end{bmatrix} \quad (1)$$

The subscripts I and II denote the primary and the secondary side respectively. D_{in} and D_{out} are tube inner and outer diameters. T_w is the wall temperature and T_b is the bulk temperature of the fluid. Its determination has been derived from the enthalpy jumps in each zone, which can be obtained from the information on the secondary side provided the quality at dry-out with a specific correlation (saturation minus inlet enthalpy for zone (i), dryout minus saturation enthalpy for zone (ii) etc). k α R denotes the thermal resistances (convective and conductive for cylindrical geometry). To determine α the Heat Transfer Coefficient (HTC) on the primary side and in the four secondary side zones, suitable empirical correlations have been used, as reported in Table 2. Correlations used for zone (ii), (iii) and (iv) are not validated for helical geometry, but these have been used anyway because of the lack of specific correlations in open literature.

The system in eq. (1) has been solved for each zone with a Matlab routine. An iterative procedure was applied, because of the presence of non-linear terms. Then, the energy balance in eq. (2) provides the value of the total length L of the jth zone:

$$\frac{1}{R_w} L_j \left(T^{I}_{wj} - T^{II}_{wj}\right) = \dot{m}^{II} \Delta h^{II}_{j} \quad (2)$$

Table 2
Empirical correlations used to determine HTCs.

Primary side	Secondary side
All zones – Zukauskas (Žukauskas, 1987) correlation for heat transfer coefficient of single-phase fluid in cross flow over a bank of tubes.	**Zone (i)** – ESDU (ESDU, 2001) correlation for single phase heat transfer in curved tubes. **Zone (ii)** – Chen (Chen, 1966) correlation for heat transfer of two-phase turbulent steady flow. **Zone (iii)** – Groeneveld (Groeneveld, 1973) correlation for heat transfer in post dry-out zone. **Zone (iv)** – Hadaller and Banerjee (Hadhaller and Banerjee, 1969) correlation for heat transfer to superheated steam. **Critical Heat Flux –** Ruffel (Ruffel, 1974) correlation to predict dryout quality in helical tubes

The term $\dot{m}_{II}$ is the secondary flowrate divided by the total number of tubes, which depends also on the number of rows, and Δh_{jII} is the increase of fluid specific enthalpy in the jth zone. The results for the two cases simulated (two and four SG modules) are reported in Fig. 3. The graphics show the length of SG tubes needed to transfer the whole thermal power for number of rows between 30 and 65. The SG is considered feasible if this value is lower than the available average length of the tubes, which slightly varies with the number of rows. Calculations with total or half primary flowrate, with respect to IRIS operating value, are also shown. LPA calculations reveal that, in principle, the outer diameter of the helical SG module can be lower than 5 m. Hence, it will be possible to define a suitable value for the primary flowrate, which optimize the RPV diameter and the head of primary pumps.

The results of the LPA have been verified with 1D system code analysis, using Relap5 system code and benchmarking versions Mod3.2 and Mod3.3. A SG with 45 rows and 5 m diameter has been modeled. The Relap5 simulations adopt the same operating and boundary conditions of the LPA calculations. The model does not consider the curvature of the tubes, since Relap5 does not include correlations for helical geometry. Quite good qualitative agreement between LPA and 1D approaches has been found (Fig. 4), although discrepancies between predictions of Mod 3.2 and Mod 3.3 will require further detailed investigations. The preliminary analysis provides reasonable evidence that the layout of the SG can be suitable for the concept of the IRIS-160, with a RPV internal diameter lower than 5 m.

2.5. Primary pumps

For the IRIS-160 the use of four axial spool-type pumps has been assumed. Pumps would be placed above the SG modules, in the annulus between the barrel and the RPV. In the 4 SG modules - 8 headers configuration, each pump is positioned between two upper headers. Overall dimensions of pump and diffuser is below 1.5 m height, 1 m width and 1 m depth. At this preliminary stage, no pump model is chosen.

2.6. Pressurizer

The IRIS pressurizer (Barroso et al., 2003) was integrated into the upper head of the RPV. The pressurizer region is defined by an insulated, inverted top-hat structure that divides the circulating reactor coolant flow path from the saturated pressurizer water. The total volume available is much larger in comparison with typical PWR design (1.6 times larger than AP1000 pressurizer). Thus, IRIS did not require sprayers, whose implementation in an integral configuration would be challenging. The IRIS-160 preliminary pressurizer design has been made keeping the same volume/power ratio of IRIS: basically, IRIS-160 needs half the pressurizer volume of IRIS. Anyway, to reduce the total height of the reactor, the shape of the dome is not spherical, but ellipsoidal. With this configuration, the necessary volume for the pressurizer (roughly 40 m^3) can be obtained with an elliptic dome with 4.7 m base diameter and less than 2 m height.

2.7. Layout

The assembly of the primary components is shown in Fig. 5. The total height of the integral RPV has been estimated and in principle it seems possible to keep it below 13 m. Similarly, the integral layout has also the potential to keep the RPV diameter below 5 m. Table 3 shows the details of height and diameter calculations. Final design sizes depend on the definition of operating flowrate and on safety considerations.

3. Basic safety strategy

The safety target for the submerged SMR concept is to implement, for decay heat removal operations, a fully passive safety approach, which does not require AC power or human interventions and can rely on the water surrounding the containment as a permanent and infinite heat sink. The achievement of this goal would practically allow eliminating the Fukushima-like accident scenarios. Scientific-based arguments are needed to assess that passive safety systems are well designed and can ensure the safe cooling of the fuel rods for an indefinitely long grace period.

The most promising set of safety systems refers to: (i) two (or four, to be defined by PSA considerations) trains of Emergency Heat Removal Systems (EHRS), i.e. two-phase flow natural circulation loops, each one connecting one in-vessel helical-coil SG module to two ex-hull condensers; (ii) a pressure suppression pool (safety tank), with direct injection lines to the RPV and to the reactor containment; (iii) the reactor containment (dry-well), which offers steam condensation capability on the metal surface in contact with the external water, (iv) two trains of in-pool heat exchangers/condensers, directly connected to the integral RPV.

The safety procedure adopts, in an "intact primary" (non-LOCA) scenario: (a) the suppression pools, to depressurize the primary system + (b) the passive EHRS, to reject the decay heat to the infinite

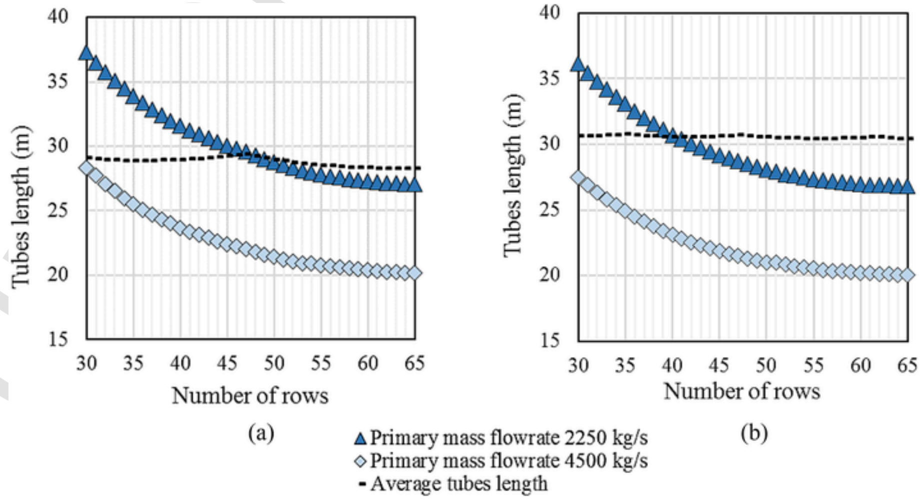


Fig. 3. Required tube length necessary to transfer 500 MWth from primary to secondary side for (a) two SG modules/four headers and (b) four SG modules/eight headers.

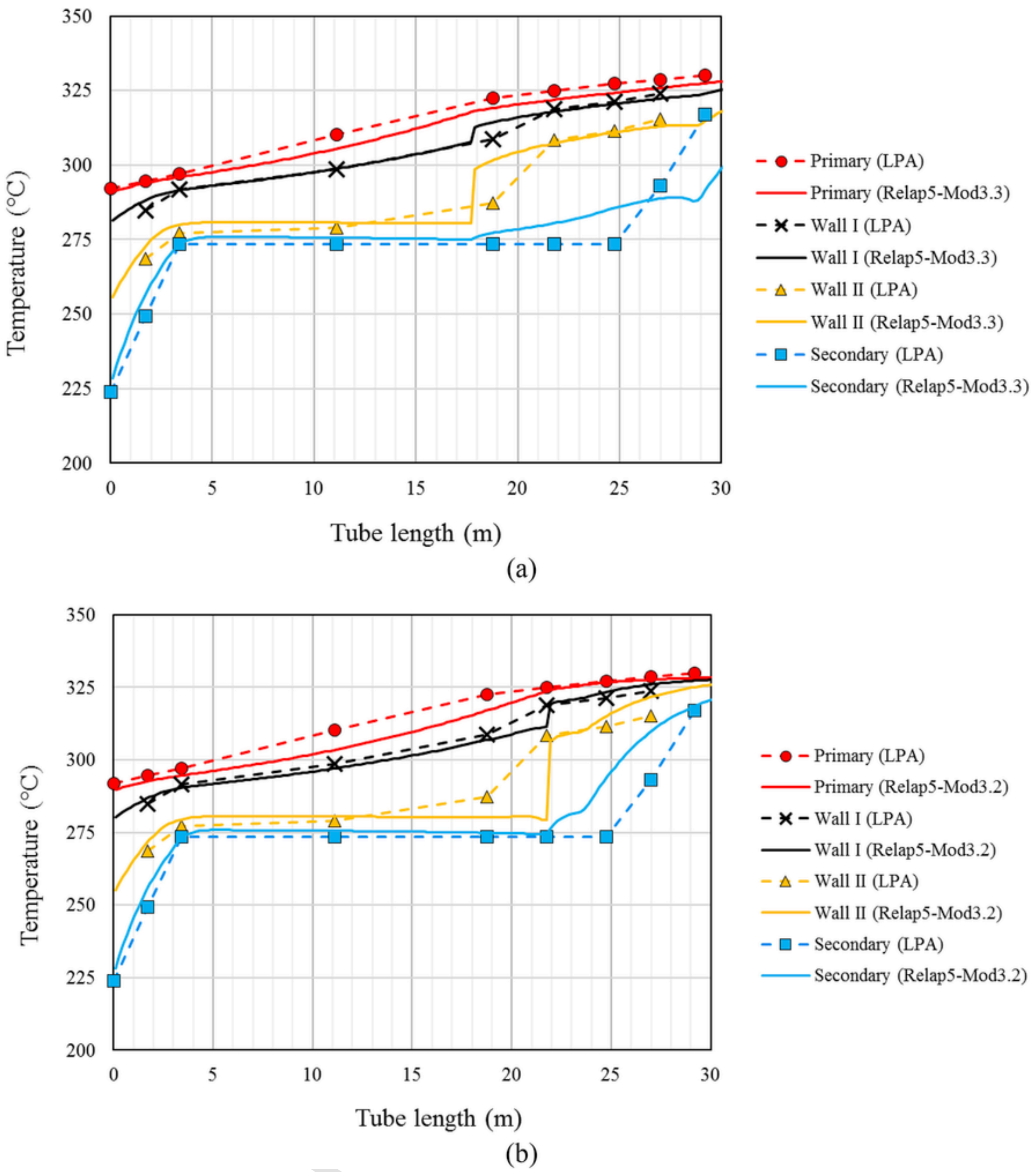


Fig. 4. Temperature profiles of the scaled SG at 15.5/6.2 MPa and 2250 kg/s, predicted by Relap5 Mod3.2 (a) and Mod3.3 (b), and compared with LPA approach.

heat sink (sea or lake) or (c) in-pool heat exchangers, to reject the decay heat to the suppression pool.

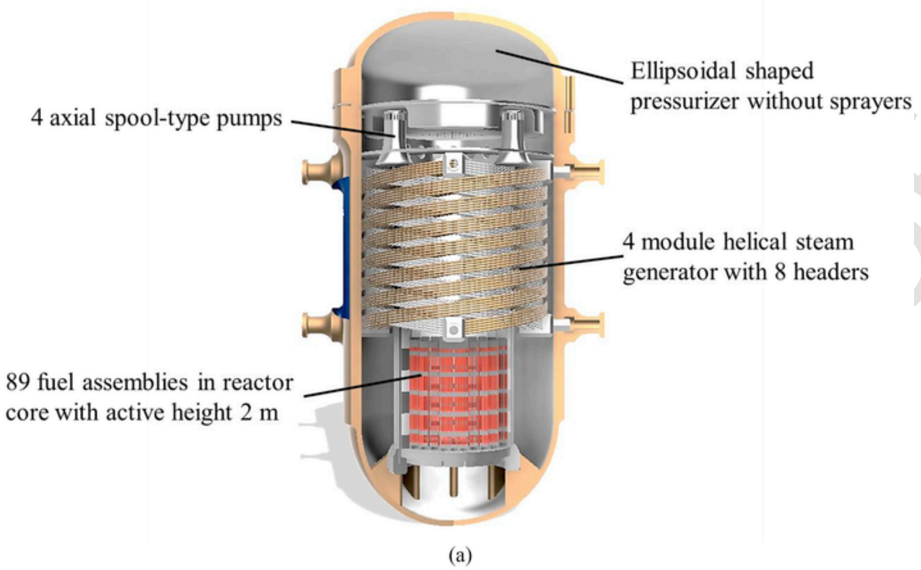
In a "non-intact primary" (LOCA-like) scenario: (a) + (d) direct injection lines to the integral RPV and to the dry-well + (e) flooding of the dry-well section of the hull and condensation on the inner wall of the containment.

The two safety strategies are sketched in Fig. 6. Thanks to the integral layout, the large break LOCA accident is prevented by design, therefore the "non-intact primary" scenario refers only to small break LOCAs, e.g., in case of rupture of a Direct Vessel Injection line.

According to a Fukushima-like scenario, the reference accident is only the Station Black-Out (SBO), since the concurrent Loss of Ultimate Heat Sink (LUHS) is assumed as practically impossible. Hence the specific accident scenarios to be investigated have been selected according to one single criterion: the integrity (or not) of the primary circuit. In case of an "intact primary" (non-LOCA-SBO) accident, the EHRS is the key passive safety system, while for a "non-intact primary" (LOCA-SBO) scenario, the hull or submerged containment plays the main role. The latter represents also a backup strategy in case of failure of other safety systems. The entire safety strategy relies on the demonstration that this process can be effective also months/years after the reactor scram, when decay power is very low. Santinello et al. (Santinello et al., 2017b) have studied the long-term cooling scenario after a LOCA through the submerged containment with a numerical analysis, showing the good response of the system.

4. Simulation of a Station Black-Out scenario

Station Black-Out event (SBO) occurs in case of complete failure of both off-site and on-site AC power sources. In this scenario, decay heat can be transferred both to in-pool and ex-hull heat exchanger. In-pool heat exchanger works in a protected environment, while the ex-hull condenser is exposed to corrosion and deposition of biofouling. How-



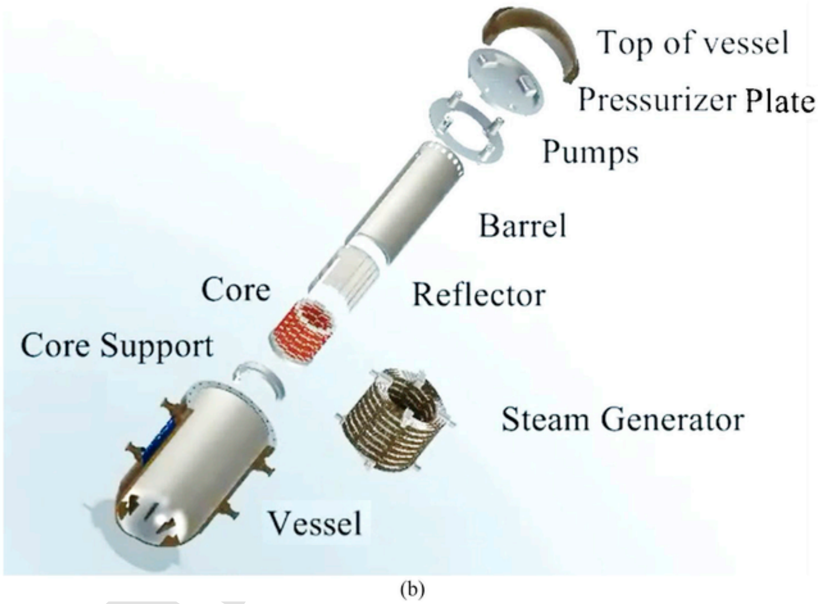


Fig. 5. Assembly (a) and components (b) of IRIS-160 reactor layout.

Table 3
Summary of estimated lengths and diameters of primary components.

RPV Height		RPV Diameter
RPV thickness ≈ 0.15 m		Core ≈ 2.75 m
Lower plenum ≈ 1.20 m		Barrel ≈ 2.85 m
Reactor core ≈ 3.20 m		Steam Generator ≈ 4.75 m
CRDM ≈ 5.50–6.00 m	Steam Generator ≈ 4.20 m Pumps ≈ 1.50 m	**Outer diameter ≈ 5.25 m**
Pressurizer (including plate) ≈ 2.00 m		
RPV thickness ≈ 0.15 m		
Total height ≈ 12.40–12.70 m		

ever, direct seawater heat transfer is more effective, since the temperature of the seawater is constant throughout the whole transient.

A numerical investigation of SBO scenario has been performed with Relap5-Mod3.3. In the simulation case, after the reactor scram decay heat removal is demanded only to the EHRS, i.e., the natural circulation loop connecting the integral SG module with the ex-hull condenser in direct contact with seawater. The RELAP5 model, set up also by exploiting the experience of a previous work (Ricotti et al., 2002), consists of: (i) the primary circuit, which includes the core, the pressurizer, the primary side of the SG and other minor components; (ii) the secondary circuit, which includes the secondary side of the SG, the EHRS exchanging directly with seawater, a water tank and connecting piping. (Fig. 7). As in paragraph 2.4, the model does not consider the helical geometry of the SG.

The seawater surrounding the condenser has not been simulated, but a convective boundary condition has been imposed on the external

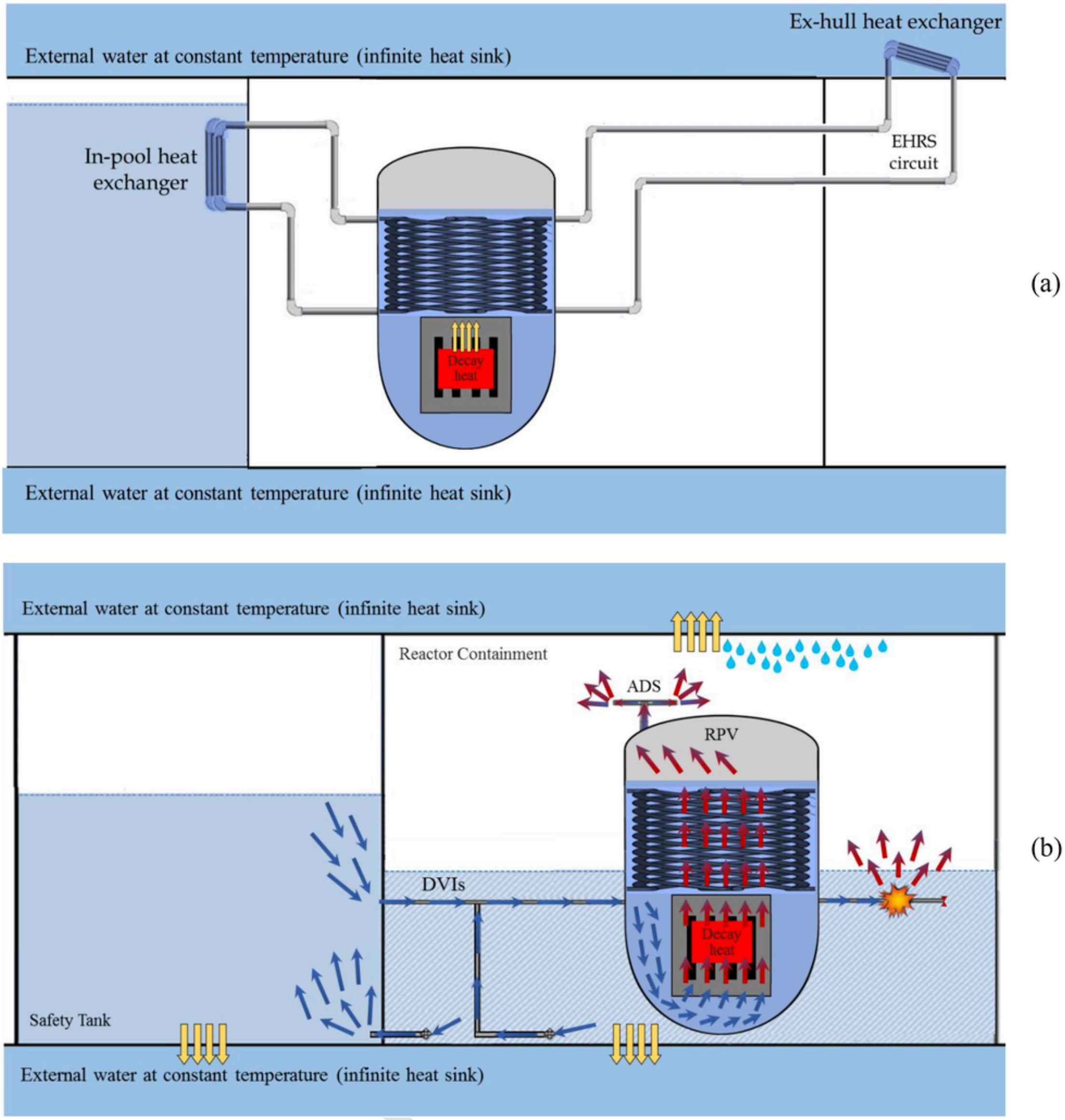


Fig. 6. Principles of safety strategy for intact (a) and non-intact (b) primary system scenarios (dimensions are not representative).

surface of the condenser. External HTC has been calculated for single-phase natural circulation with Churchill & Chu correlation (Churchill and Chu, 1975) from horizontal tubes. If tube surface temperature is 5 °C higher than saturation temperature of seawater, HTC has been calculated with Palen correlation (Palen et al., 1972) for nucleate boiling heat transfer from a horizontal tube bundle. Seawater at 20 °C and 0.6 MPa has been considered. The power source in the core has a total initial value of 500 MW_{th} and it has a cosine-shape axial distribution. After 1500 s of nominal operation, SBO occurs: pumps stop operating, pressurizer control is disabled, and some trip valves isolate the turbine sector and connect the SG secondary side to the EHRS. Reactor is scrammed, and power generation follows the decay curve. Natural circulation flows are established in primary and secondary loops and a 5-hour-long transient has been simulated.

Relap5-Mod3.3 simulation predicts that the nominal configuration can remove the decay power from the core (Fig. 8). Natural circulation flows transfer the decay heat to the seawater without risks of primary coolant overheating and core uncovering (Fig. 9). Results provide a preliminary verification of the working principle of the EHRS and show the great potentialities of passive safety systems exploiting a heat sink at constant temperature. Thermal power rejected to the exterior is always greater than decay heat and after about 6000 s the heat flow becomes higher at the seawater condenser than at the SG. This means that in that period the secondary circuit is accumulating heat. During this period the quality at the outlet of the SG is around steam saturation (Fig. 10), while it decreases in the following parts of the transient. For an indefinitely long time, thermal equilibrium would be reached. The pressure curves shown in Fig. 11 have a monotonic decreasing trend. At the end of the simulation time, the pressure decreases to very low values. This is probably due to the effect of the very cold heat sink and, if verified, it could allow avoiding the need to actuate an Automatic Depressurization System (ADS) for this type of scenario. ADS would anyway operate in case of failure of the EHRS.

5. Challenges for submerged SMRs deployment

To achieve the final design, licensing and commercialization of submerged SMRs, some critical issues still require to be addresses. Main issues include (i) design of a boron free core, (ii) remote operating and control, (iii) refueling and maintenance, (iv) licensing procedures, (v)

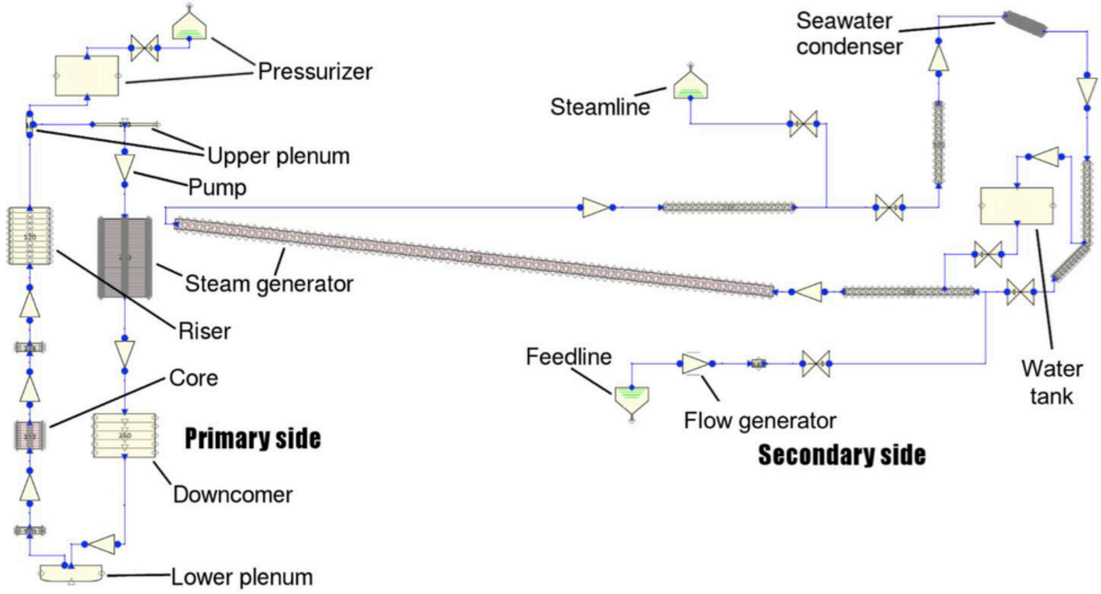


Fig. 7. Relap5 modeling of primary and secondary sides.

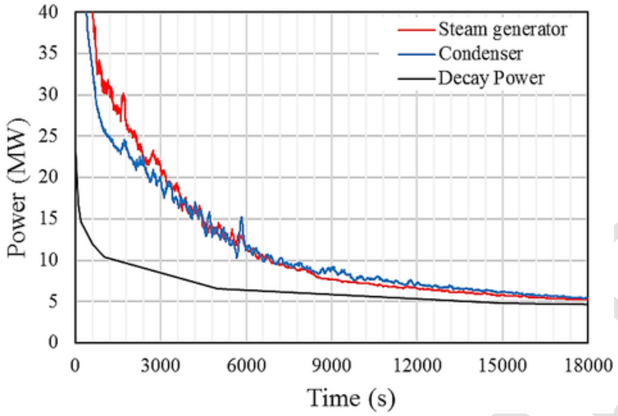


Fig. 8. Comparison among power in core, SG and EHRS.

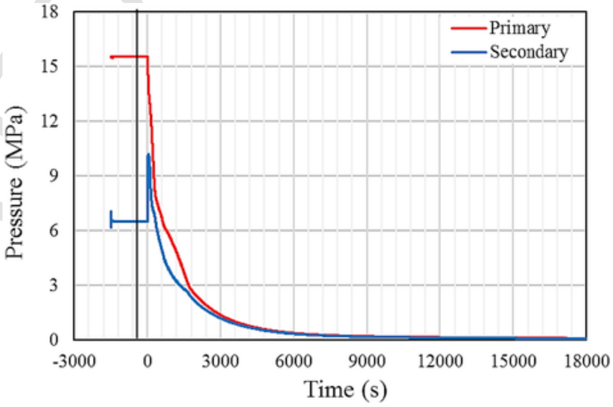


Fig. 10. Primary and secondary pressure.

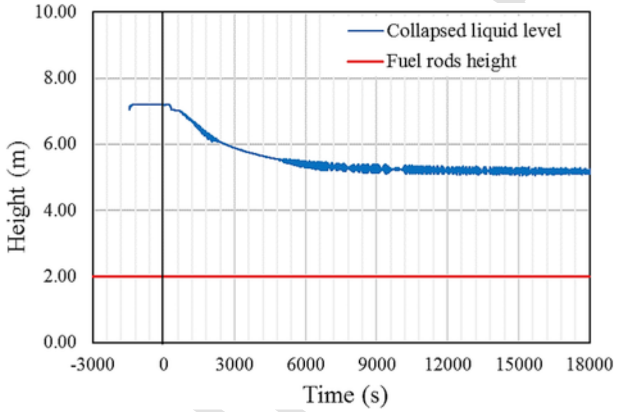


Fig. 9. Collapsed liquid level in core barrel (zero is the base of active core).

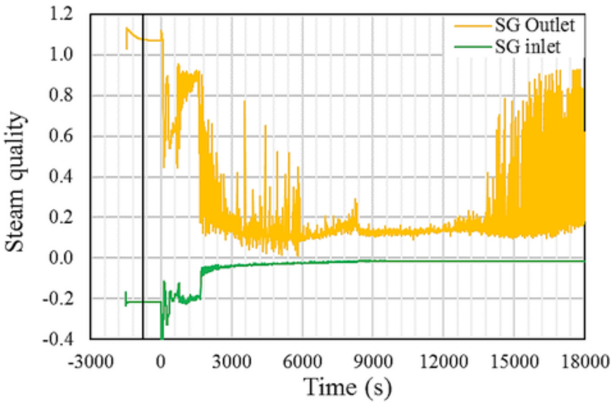


Fig. 11. Steam quality at SG inlet and outlet.

international regulation, (vi) economic sustainability, (vii) public acceptance.

(i) *Design of a boron free core.* The use of soluble boron in a submerged SMR has been discussed by Ingremeau and Cordiez for the Flexblue case (Ingremeau and Cordiez, 2015). They observed that the recycling system of borated water is voluminous and requires frequent maintenance. Therefore, it cannot be suitable for an underwater reactor, where the available space is limited, and maintenance cycles must be quite long. They noticed also that a design based on boron control can lead to criticality in case of a severe scenario with seawater flooding the reactor compartment, if boron is used to maintain cold shutdown. The design of soluble boron free core needs to define an accurate strategy to safely manage the cold shutdown, the control rod ejection and other type of reactivity accidents, the Xenon stability, the load following and the reactivity swing.

(ii) *Remote operating and control.* A sea-based SMR operating few kilometers far from the shore would need a remote-control system. The distance between the reactor site and the control room is much larger than in conventional power plants and the control system would require more components and cables. There are more variables that can cause the damage/failure of the system and disturb the control operations. To ensure the reliability of remote control operations, ad-hoc I&C systems need to be developed and tested. Anyway, an important work has been performed by DCNS for the Flexblue reactor. The nominal communication system in Flexblue is through submarine cables. Emergency system works via radio links, and ultimately via an acoustic link. This strategy is based on a diversification principle. However, the use of wireless I&C equipment is still considered less reliable than cable technology and more exposed to security breaches (Internationl Atomic Energy Agency, 2017).

(iii) *Refueling and maintenance.* Flexblue designers stated that the submerged power unit has no staff on board during operation, but it is accessible via submarine vehicles and the containment is provided with access hatches, so that light maintenance and inspection can be performed onboard while on the seafloor (Haratyk et al., 2014). However, the position of the hull on the seafloor is challenging with respect to the access to the reactor for ordinary maintenance: the feasibility of all routine operations with automatized systems should be verified. Refueling and large maintenance operations would need to be done in factory, moving the reactor from the site and then extending the stop period. This could be solved in principle by assuming a replacement of the whole reactor module, in case of heavy maintenance. Given that maintenance operations are burdensome, it would be very important to define maintenance strategies in strict correlation with advanced on-line monitoring systems and assess the reliability of the system and predict incipient failure conditions. A review of current technologies for this purpose is given by Coble et al. (2012).

(iv) *Seismic assessment.* To prevent from the seismic risk, a submerged SMR needs to be isolated from the seafloor and isolation systems specific for a marine application must be designed. Kim et al. (2014) studied the case of an offshore reactor operating on a Gravity-Based Structure (GBS) and introduced a base isolation system to reduce acceleration by adjusting the total weight of the GBS. The study is very interesting, since it addresses the seismic issue of an offshore reactor. However, the case of a submerged SMR moored on the seabed, like Flexblue, has peculiar features that require not only structural investigations of the reactor and isolation from the ground, but also geological analyses of the site. One of the main concern in case of a submarine earthquake is the stability of the seabed. The choice of the site would require the accurate analysis of the composition of the soil and its response in case of seismic event.

(v) *Licensing procedures.* Currently, little or no experience about the licensing of offshore SMRs is owned by the nuclear industry. The main reference on this field is the floating barge KLT-40, which is under construction in Russia (Kuznetsov, 2012). In almost all countries, licensing regulation has been developed for large power plants, therefore procedures still need to be adapted to SMRs (Ramana et al., 2013). An important effort is under way at IAEA level: the SMR Regulator's Forum has been established in 2015 (http://www-ns.iaea.org/t). Moreover, within the World Nuclear Association, the CORDEL Working Group in 2013 established the Small Modular Reactor Ad-hoc Group (SMRAG), to elaborate a path towards harmonized and well-regulated global SMR deployment (Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group, 2015). Finally, a reference work on SMR licensing issues was authored by Soderholm et al. (Söderholm et al., 2014).

(vi) *International regulation.* Recently, IAEA (Internationl Atomic Energy Agency, 2013) developed a preliminary study about this topic. The analysis addressed several challenges of the deployment of transportable nuclear power plant from the viewpoints of legal issues. These challenges include: nuclear safety, radioprotection, security, safeguards, liability. Within this context, for submerged SMRs the transportation of the nuclear power plant containing fissile material and irradiated fuel represents a key challenge and it is not fully addressed yet in international regulation.

(vii) *Economic sustainability.* The economic sustainability of submerged SMR concept is not differential with respect to on-shore SMR designs, since it relies as well on modular investment and on the possibility to build the reactor in factory and not on site. However, O&M costs for submerged SMRs could be considerably higher than for conventional on-shore nuclear power plants, especially for the deployment of the first power units. Haratyk et al. (2014) estimated 100 €/MWh as targeted energy cost for Flexblue. This price is high if compared with larger nuclear and fossil fuel plants, but can become competitive in some niches of the energy market, e.g. in zones where there are energy needs but the land is scarce, isolated or not suitable for the construction of a power plant.

(viii) *Public acceptance.* The presence of strong emotional and ethical concerns in non-expert population has always characterized the debate about the peaceful uses of nuclear power. Although the "submerged concept" represents an undeniable advantage for safety strategy and mitigation of severe accident consequences, the perception of the public opinion could be different. The concern that the undersea deployment is a way to escape control (Haratyk et al., 2014) and the fear of an "irreversible" sea contamination could prevent non-experts from appreciating the safety improvements brought by the submerged SMR concept, thus keeping unchanged or even reducing the level of public acceptance.

6. Conclusions

Submerged SMRs owns unique safety features, which could represent a great enhancement or a sort of ultimate solution to address Fukushima-like accident scenarios. The paper has presented the conceptual design of IRIS-160, an integral SMR sized to fit and operate in an immersed hull. The activity has addressed also the definition of reactor design and safety strategy. The IRIS layout has been used as reference and primary components have been revisited and sized in order to fit a containment with 14 m diameter. Results of preliminary calculations show that, with a helical SG placed around the barrel, the diameter of the RPV can be lower than 5 m. A basic safety strategy has been defined to face non-LOCA and LOCA accident scenarios, exploiting the surrounding water as a permanent and constant temperature heat sink. A simulation of a SBO has been performed with Relap5-Mod3.3, revealing a good response of the EHRS. In addition, the main challenges that still need to be addressed for the deployment of submerged SMR have been identified. Next steps of the investigation will require a more accurate analysis and verification of core design, especially regarding the neutronics, and working principles of the passive safety systems.

List of Acronyms

ADS	Automatic Depressurization System
CEA	Commissariat à l'Energie Atomique
CFD	Computational Fluid Dynamics
CHF	Critical Heat Flux
CRDM	Control Rods Driving Mechanism
DCNS	Direction des Constructions Navales Services
DVI	Direct Vessel Injection
EHRS	Emergency Heat Removal System
HTC	Heat Transfer Coefficient
IAEA	International Atomic Energy Agency
IRIS	International Reactor Innovative and Secure
LOCA	Loss Of Coolant Accident
LOOP	Loss Of Off-site Power
LPA	Lumped Parameter Approach
LUHS	Loss of Ultimate Heat Sink
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SBO	Station Black-Out
SCOR	Simple COmpact Reactor
SG	Steam Generator
SMR	Small Modular Reactor

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