Progress in Nuclear Energy 96 (2017) 62–75

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

External heat transfer capability of a submerged SMR containment: The Flexblue case

M. Santinello [a], M.E. Ricotti [a, *], H. Ninokata [a], G. Haratyk [b], J.J. Ingremeau [b], V. Gourmel [b]

[a] Politecnico di Milano, Dept. of Energy, CeSNEF-Nuclear Engineering Division, Via La Masa 34, 20156, Milano, Italy
[b] DCNS, 40-42 rue du Docteur Finlay, 75015, Paris, France

A R T I C L E I N F O

Article history:
Received 17 January 2016
Received in revised form
17 November 2016
Accepted 1 December 2016

Keywords:
SMR
Subsea-based
Transportable
Passive safety
CFD

A B S T R A C T

Flexblue® is a 160 MWe, transportable and subsea-based nuclear power unit operating up to 100 m depth several kilometers away from the shore. The concept is based on existing technologies and experience from the oil&gas, civil nuclear and shipbuilding industries. In a post-Fukushima world, its safety features are particularly relevant. The immersion provides inherent protection against most external aggressions including tsunamis, extreme weather conditions and malevolent actions. The vicinity and the availability of an infinite, permanent heat sink – the ocean – enhances the performance of the safety systems which, when designed to operate passively, considerably extend the grace period given to operators in case of accident. The present work investigates seawater natural convection fluid dynamics and heat transfer features, induced by the heating of Flexblue® reactor containment, to evaluate the capabilities of the system to reject the decay power to the exterior in case of an accident. A preliminary lumped parameters approach has been adopted, revealing that the large diameter of the hull (14 m) is such that ranges of validity of empirical correlations for natural convection heat transfer are always exceeded and conditions for their correct application are not satisfied. Hence, a 2D, unsteady CFD analysis has been performed to simulate the natural convection flow in the ocean, thus obtaining predictions for heat flux distribution, hull superficial temperature profile and heat transfer coefficient. Both CFD sensitivity and parametric analyses have been carried out, even if within a 2D approach, to limit the computational burden. The results showed that the heat transfer process is globally satisfactory to ensure the safe cooling of the reactor. A 3D approach and an experimental campaign aimed at validating the CFD results have been planned.

1. Introduction

The current offer of nuclear power plants (NPPs) is mainly composed of large-scale units rated at more than 1000 MWe. These units fit well to the needs of large power grids such as in Europe or China, where big utilities can afford the initial investment required for the construction. However, these units do not fit well in smaller grids, where they would represent more than 10% of the installed capacity. They underestimate the difficulties of utilities to afford large investments, and the related high premium that bankers and investors demand on such projects, where cost and delay overruns are common (Kessides, 2012; Thomas, 2012). In consequence, the financing of a large nuclear reactor is complicated for most utilities. The competition with fossil-fueled units and, in some areas, with renewable energies, is harsh.

To address these challenges, the nuclear industry is today developing small modular reactors (SMRs) (Vujic et al., 2012). SMRs would facilitate the financing thanks to a more progressive investment, a shorter construction time and an accelerated return on investment (Rosner and Goldberg, 2011). The Levelized Cost of Electricity (LCOE) of SMRs compensates the 'economies of scale' by 'economies of number' and by simplifying the reactor design (Boarin et al, 2012; Lokhov et al, 2011). Yet these units' cost still suffers from significant civil work, since reactors are often bunkered underground (Xie, 2012).

Besides, there happens to be significant energy needs in regions of the world where land is scarce, isolated or just unsuitable for the construction of a nuclear reactor. This is for instance the case of

* Corresponding author.
E-mail addresses: marco.santinello@polimi.it (M. Santinello), marco.ricotti@polimi.it (M.E. Ricotti), hisashi.ninokata@polimi.it (H. Ninokata), gharatyk@mit.edu (G. Haratyk), jeanjeacques.ingremeau@dcnsgroup.com (J.J. Ingremeau), vincent.gourmel@dcnsgroup.com (V. Gourmel).

http://dx.doi.org/10.1016/j.pnucene.2016.12.002

remote areas with large natural resources, islands or highly populated areas under the threat of natural hazards. Transportable offshore nuclear power plants, such as the floating barge Akademik Lomonosov (Kuznetsov, 2012) aim at addressing the first case. This barge, under construction in Russia, will be supplying North-East Siberia in energy without the need for frequent refueling in gas, as it is the case today.

An alternative solution to the floating transportable plant consists in setting the reactor underwater, on the seafloor. Electric Boat (General Dynamics Electric Boat Division, 1971) and J. S. Herring, (1993) investigated such subsea reactor designs in the 1970's and 1990's respectively. These projects stayed at the paper project stage. The progress in subsea oil&gas technologies, submarine cables for offshore renewables and in shipbuilding techniques make offshore power reactors more feasible today than before, with an increasing interest towards that option (Buongiorno et al., 2016). They appear attractive as the Fukushima accident calls our nuclear industry to better consider extreme external events in the design of NPPs.

Based on its experience in the design, fabrication, maintenance and dismantling of nuclear-powered submarines and ships, DCNS is developing a subsea, transportable nuclear power plant named Flexblue®.

2. The Flexblue® concept

2.1. Module main features

Flexblue® is a subsea and fully transportable modular power unit (Haratyk et al., 2014). It supplies 160MWe to the grid via submarine cables. It is immersed down to a hundred meter depth, a few kilometres away from the shore, within territorial waters (Fig. 1).

Flexblue® is entirely manufactured in factories and assembled in a shipyard per naval modular construction techniques. The module, a cylindrical hull of about 150 m long and 14 m diameter, is brought on site by transport ship and moored on the seafloor, where production takes place. The module is monitored, protected but also possibly operated from an onshore control center. It is permanently accessible via a submarine vehicle that connects to access hatches, so that light maintenance, inspection and operation can be performed onboard while on the seafloor.

Every 3 years approximately, electricity production stops for refueling. The module is removed and transported back to a coastal facility, which hosts the spent fuel pool.

Major overhaul occurs every 10 years, i.e. every three fuel cycles. Several Flexblue® units can operate on the same site and hence share the same support systems. The main characteristics and reactor data of a Flexblue® unit are listed in Table 1.

Flexblue® uses typical pressurized water reactor technology, which benefits from a considerable experience in commercial power plants and naval environments. The reactor utilizes only civil proven technologies: although adaptation of components to the particular design is required, no innovative or risky development is expected.

DCNS and its partners are currently considering different types of reactors: a loop-type design called 'reference design' is presented here for illustration purpose. The reference design exhibits two primary loops: two primary coolant pumps and two recirculation steam generators. The main safety and auxiliary fluid systems are located in the reactor section and the turbine section. In addition to the reactor section, the Flexblue® module hosts the turbine & alternator section, the aft section and the fore section. These two latter sections accommodate: emergency batteries, a secondary control room, process auxiliaries, I&C control panels, spares, living areas for a crew, and emergency rescue devices.

Redundant main and auxiliary submarine cables transport electricity as well as information between the module and the onshore control center.

2.2. Safety, security and environment

The Flexblue® concept not only complies with the latest European safety standards (Generation III + reactors) but also offers room for significant breakthroughs in nuclear safety. The safety of Flexblue® indeed benefits from its manufacturing process and from the submerged environment at several levels. Firstly, the quality of manufacturing in a factory is enhanced. Secondly, most external hazards, whether they are natural or from human actions, are diminished underwater. Extreme weather conditions (e.g. wind, storms, snow, floods, drought, heat waves), tsunamis, earthquakes (thanks to appropriate engineering features) have no or little impact on the plant. Last but not least, the availability and infinity of the heat sink, in relation with passive safety systems, provides a long and efficient performance of the reactor safety functions without need for external power. The likelihoods of core damage and large early release of radioactivity are extremely low.

The reactor containment (reactor sector) is bounded by the hull on the sides and the reactor sector walls on the front and on the back (Fig. 2). A large share of the metal containment walls are therefore in direct contact with seawater, which provides very efficient containment cooling without the need for containment spray or cooling heat exchanger. This paper actually focuses on the external side of heat transfer and shows the potentiality of such concept.

Two large tanks of water – the safety tanks – act as intermediate heat sinks, as pressure suppression pools (like in BWRs) and/or as sources of coolant injection depending on the accident scenarios.

In case of an accident, active systems are used if AC power is available. If not, passive safety systems are actuated automatically when emergency set points are reached. The passive safety strategy is based on reaching a safe shutdown state via passive means. As an example, in case of Loss Of Flow Accidents (LOFA), the reactor is shutdown and natural convection closed loops activate to provide emergency core cooling, to transfer decay heat to the environment: emergency heat exchangers both on the primary side (immersed in the safety tanks) and on the secondary side (directly immersed into seawater) are available. In case of LOCA scenarios, several cold water injection sources restore core coolant inventory: core make-up tanks at high pressure, accumulators at medium pressure and gravity driven safety tanks at low pressure. Low primary pressure is achieved through automatic depressurization system. Condensation occurs on the containment walls. Once gravity injection tanks empty, recirculation sump screens actuate to collect the condensates at the bottom of the containment and reinject them into the core. No pump is required and heat is ultimately evacuated through the containment walls to the environment.

The large surface area of the naturally-cooled containment wall in contact with seawater ensures very efficient heat removal, as this study will show. Sump pH control and inertisation prevent containment damage from corrosion and hydrogen flammability respectively.

The containment is designed to sustain even severe accidents with core meltdown. In this case, the mitigation strategy consists in in-vessel corium retention assisted by an ex-vessel passive core cooling. In the unlikely catastrophic hypothesis where all barriers would have failed, radioactive elements would be released into seawater. However, unlike an atmospheric release of a land-based reactor (Ramana et al, 2013), no short-term emergency counter