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Original Article

Technology Selection for Offshore Underwater Small Modular Reactors

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ABSTRACT

This work examines the most viable nuclear technology options for future underwater designs that would meet high safety standards as well as good economic potential, for construction in the 2030–2040 timeframe. The top five concepts selected from a survey of 13 nuclear technologies were compared to a small modular pressurized water reactor (PWR) designed with a conventional layout. In order of smallest to largest primary system size where the reactor and all safety systems are contained, the top five designs were: (1) a lead–bismuth fast reactor based on the Russian SVBR-100; (2) a novel organic cooled reactor; (3) an innovative superheated water reactor; (4) a boiling water reactor based on Toshiba's LSBWR; and (5) an integral PWR featuring compact steam generators. A similar study on potential attractive power cycles was also performed. A condensing and recompression supercritical CO_2 cycle and a compact steam Rankine cycle were designed. It was found that the hull size required by the reactor, safety systems and power cycle can be significantly reduced (50–80%) with the top five designs compared to the conventional PWR. Based on the qualitative economic consideration, the organic cooled reactor and boiling water reactor designs are expected to be the most cost effective options.

1. Introduction

With the rise of interest in small modular reactors (SMRs), DCNS in France is working on a 160-MWe offshore underwater reactor. The DCNS underwater power plant, called Flexblue, resembles a nuclear submarine without the ability to self-propel [1]. Flexblue would be anchored to the seabed compared to a terrestrial reactor. An undersea and transportable reactor has several advantages. First, the ocean heat sink provides an accessible near-infinite source of water for passive safety cooling of the core in the event of loss of normal reactor system cooling. Second, the underwater offshore siting of the reactor allows installation in areas normally interdicted to large land-based plants, for instance: regions near dense populations, with harsh weather and climate, or subject to natural threats such as tsunamis. Third,

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Nomenclature

BWR	boiling water reactor
CRD	control rod drive
ISP	internal suppression pool
IXAF	internally and externally cooled annular fuel
LBFR	lead–bismuth fast reactor
LOCA	loss of coolant accident
LWR	light water reactor
OCR	organic cooled reactor
PWR	pressurized water reactor
RPV	reactor pressure vessel
SCO_2	supercritical CO_2
SMR	small modular reactor
SWR	superheated water reactor

similar to most land-based SMRs, the reactor is entirely manufactured in a factory or shipyard, which could save construction time and money. It eliminates the massive concrete structures needed on land including the basemat and containment walls. Transportability may allow flexible installation and a new business model for the nuclear industry, where a plant could change owner and location several times in its lifetime [2]. Buongiorno et al. [2] provide a more detailed discussion on the advantages of offshore siting. The major drawback of such a plant is its complicated maintenance and refueling operation.

The Flexblue design is based on a standard pressurized water reactor (PWR) technology. While PWRs are the dominant technology for land-based nuclear power plants, they may not be the optimal choice for the offshore underwater setting. The work reported here is the result of a comparative study of promising designs that may lead to improved performance in a future seabed-anchored SMR based on certain goals and constraints. Previous published work [3] focused on narrowing the promising reactor technologies from 13 to five and viable advanced power cycle systems from six to three. The design priorities used to narrow down the 13 technologies for this study were in the following order of decreasing importance:

- ➢ Safety: Ability to fulfill the safety objectives (reactivity control, decay heat removal and radioactivity containment) by passive means for an indefinitely long period.
- ➢ Compact reactor layout, to maximize power density of the plant
- ➢ Achievement of a long fuel cycle to increase plant availability.
- ➢ High thermodynamic efficiency of the power conversion cycle
- ➢ High compactness of the power conversion cycle (turbine–generator cycle)
- ➢ High dual-use resistance: this includes weapons proliferation resistance and unsuitability for military applications (including propulsion).
- ➢ Sufficient technology maturity to be deployable by 2030–2040.

The following design constraints were imposed on this study to meet the desired performance goals:

- ➢ 160 MWe power output
- ➢ The hull (containment) dimensions are limited to 15 m in diameter due to manufacturing constraints by DCNS and 20 m in vertical height to assure the hull is sufficiently submerged in 30-m-deep water.
- ➢ The reactor is to be deployable in 30–100 m of water.
- ➢ The safety systems must be able to operate for an indefinitely long period using passive decay heat removal.
- ➢ In case of accidents, releases of radioactivity outside the hull must be prevented.
- ➢ The fuel U^{235} enrichment must remain below 19.75% to mitigate proliferation concerns.
- ➢ The desired fuel cycle length is >5 years but <9 years due to unavoidable maintenance needs per DCNS recommendation. The challenge of maintenance-free extended operation (>2 years) along with potential solutions for the IRIS SMR design has been investigated in the past [4]. While a 4-year fuel cycle was deemed feasible for the IRIS SMR design, future detailed study on feasibility of a 5–9 year fuel cycle length for 2030–2040 deployment time frame needs to be performed.

The initial 13 nuclear technologies were assessed with respect to the various priorities and constraints. A summary of this selection process is listed in Table 1. The achievement of safety and compact reactor design were the two top priorities. A limitation on the vertical containment height (20 m) and a minimum fuel cycle length of 5 years were the most restrictive constraints. Among the reactor concepts considered, the sodium fast reactor was eliminated due to incompatibility of sodium with water, which could occur in case of catastrophic failure of the hull. The gas fast reactors [He and supercritical (S)CO_2-cooled designs] were eliminated due to the difficulty to achieve a fully passive safe design. Four concepts (supercritical water, molten salt fuel, salt cooled, and gas-cooled high-temperature thermal reactors) were eliminated due to an inability to achieve >5 year refueling intervals while achieving satisfactory economic operation by 2030–2040. The CANDU design was eliminated due to requiring a larger hull size than the design constraint. The five concepts that remained viable according to the adopted design priorities and constraints were: the PWR; the boiling water reactor (BWR); the superheated water reactor (SWR); the lead–bismuth fast reactor (LBFR); and the organic cooled reactor (OCR). For the BWR, the Toshiba LSBWR and for the LBFR, the Russian SVBR-100 were chosen as reference designs that can be used without further development, while additional investigations were performed for the other three concepts. See Shirvan et al. [3] for more details regarding this selection process.

This work focuses on comparison of the top five chosen technologies with their respective advanced compact power cycles. A brief overview of the five technologies is given with more focus on the integrated PWR, the advanced version of the PWR option, since its design details have not yet been published elsewhere. The comparison to a conventional PWR design is then performed.

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